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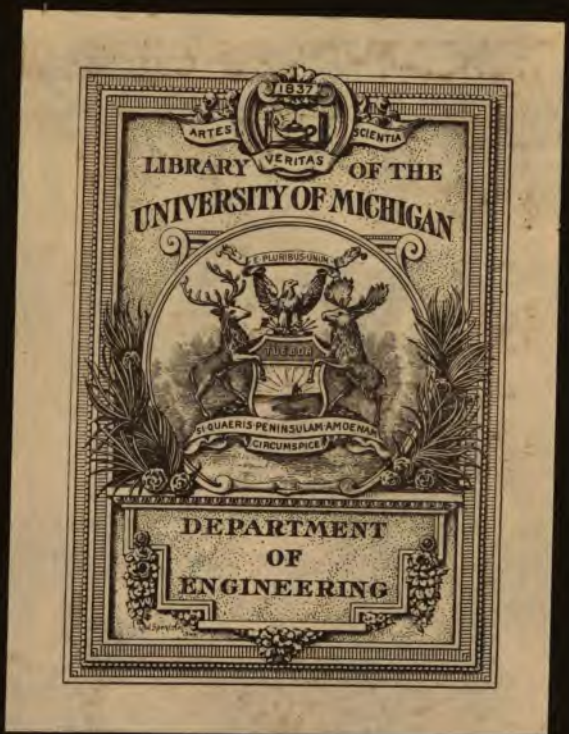
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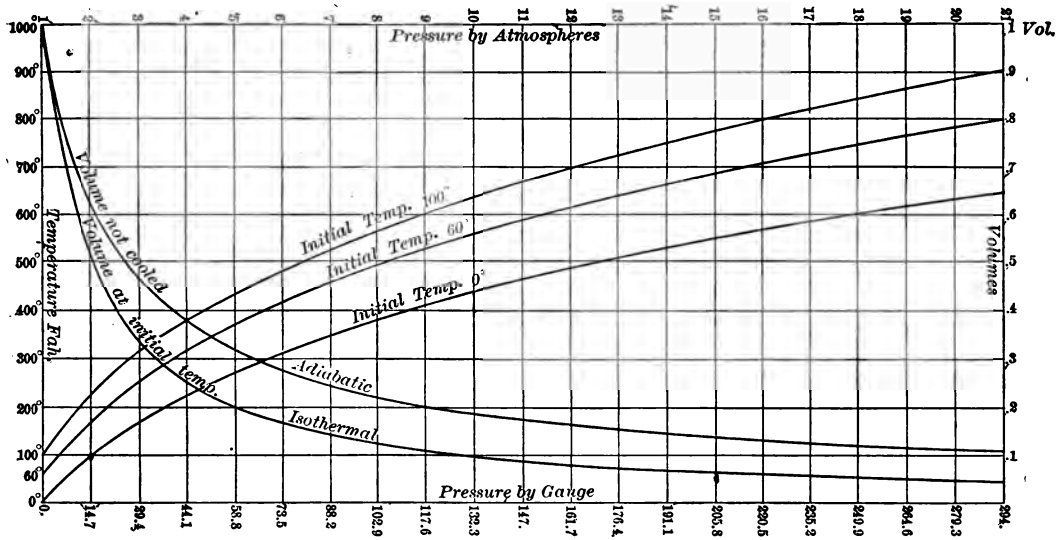

From "Compressed-Air Production," by W. L. Saunders, C.E.

Frontispiece.

COMPRESSED AIR.

PRACTICAL INFORMATION UPON

5-9.178

AIR-COMPRESSION AND THE TRANSMISSION AND APPLICATION OF COMPRESSED AIR.

BY

FRANK RICHARDS, MEM. A.S.M.E.

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PREFACE.

It is only proper to say that much of the matter contained in the following pages has appeared at intervals during the past two years in the columns of the *American Machinist.* The publication of the articles referred to and the remarks which they have elicited have served to emphasize to me the too evident fact of the general scarcity of practical information about air-compression and the uses of compressed air, and the wide diffusion of misinformation and prejudice upon this subject. In spite of it all the use of compressed air is rapidly spreading, and everywhere with satisfaction to the users. I would gladly do what I can to extend the field of its usefulness, and I have so much faith in its powers that I believe that the best of all ways to advertise it is simply to tell the straight truth about it, and that I have tried to do.

Frank Richards.

New York, May, 1895.

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COMPRESSED AIR.

CHAPTER I.

MECHANICAL VERSUS COMMERCIAL ECONOMY.

BEFORE considering the conditions under which air may be most economically compressed, having regard to the power cost alone, and the conditions relating to the transmission and application of the air, so that the most power may be realized, it seems proper to say something of the many applications of compressed air where the question of the actual power cost of the air, or of the actual amount of power realized from the air, seems to have little to do with the case. This is like asking a suspension of judgment, or a reservation of final decision upon the claims of compressed air, until the whole case has been presented; and it seems to be rather necessary, because so many have fallen into the habit of thinking only of the losses of power in the use of compressed air, and of arguing that because certain losses are proven, that therefore the employment of compressed air is not to be considered for any purpose. There are many men even in these days, and many intelligent engineers among them, who, to their own loss, will not

consider the claims of compressed air as a means of power transmission, because their minds have been so filled with this idea that its use entails enormous losses. That consideration settles it for them, and that is the libel from which compressed air suffers, so that it does not get a fair chance even to show what it can do. It is only another case of giving a dog a bad name; and in this case it is a very good dog with a very bad name. It is the worst kind of a case to set right, and often the dog dies before justice is secured. In this case, however, there is not the slightest possibility of killing the dog or of shutting him out of sight, and the public cannot fail in the end to get hold of the facts as they are.

The attitude of compressed air before the mechanical public, and especially the American mechanical public, has been a peculiar one all the way through. It has had no disinterested, all-around friends to look after its interests, nor interested ones either. There have been no men, and still less has there been any company of men, who have made the application of compressed air their business and have looked after it. Where is the General Compressed-Air Company, in fact as well as in name, performing for compressed air such functions as more than one company are performing for electricity, and why is there not such a company? Of the builders of air-compressors not one of them has been, not one of them is to this day, responsible for the economical application of compressed air *after the compression*, or apparently cares anything about it. This is not really to be wondered at, since the increase in the use of compressed air and in the demand for compressors has been so great and rapid, at least in the United States, that the compressor builders have been fully occupied in satisfying the demand,

Where compressed air has been used in this country, and where any thought has been given to economy in its use, the air-compressor, it would seem, has been almost exclusively studied and talked about. In the progress of the steam-engine it has sometimes seemed that the steam-boiler has hardly received its proper share of attention. In the existing writings upon steam-engine economy it is probably safe to say that the engine engrosses ten times as much of the matter as the boiler does. In the case of compressed air the boiler, or compressor, gets ten times as much study and discussion as the engine or motor or other apparatus which uses the air. There are such vagaries of injustice in civilized communities.

The impression which has got abroad of the waste of power in the use of compressed air has, curiously enough, been fostered and disseminated by the air-compressor people more than by any one else. We may say this with perfect safety, for it strikes so generally that it hits no one in particular. The compressed air literature accessible to the general public consists principally of air-compressor catalogues. The argument of the average catalogue runs like this: "If you are going to use compressed air for any purpose, look out for the enormous losses of power to be encountered, and which you are sure to experience, *if you don't buy our compressor.*" And the result has been that many have "caught on" to the terrible tale of the waste of power, and have helped to spread it far and wide. The argument is, of course, not maliciously meant; but it has done more work, and somewhat different work, than that which was intended.

But whether the employment of compressed air be economical or not, as far as the application of the power is

concerned, we do not propose to investigate that subject just here. We wish rather to call attention to the many applications of compressed air where this question of power economy certainly does not apply. We may say, indeed, that in a large majority of the cases in which compressed air is used the question of power economy does not apply. Even in the use of compressed air for driving rock-drills in mines and tunnels, the field which still probably employs one half of all the compressed air that is used for mechanical purposes, the question of economy, or the comparative cost of operation, so far as it might determine the employment or the rejection of the system, is not worth considering, because in this field compressed air has no competitor, unless hand-power may be said to be one. In the use of compressed air for operating the brakes upon railway trains, a service which employs a greater number of air-compressors than any other line of service in the world, economy of power is not to be considered. Although it is notorious that the compressors employed for this service use five times the steam they should use for the work done, and ten times as much steam as the best-designed air-compressors of the present day would use for the same work, there would be no thought of throwing the air-brake off the trains if those "compressing-pumps," as they are familiarly called, used double or four times as much steam to do their work as they use now. Any one of several collateral considerations may easily take precedence of or assume greater weight and importance than the question of power economy in determining the employment of compressed air. The cases are few in which it is employed merely as a means of power transmission, and in competition with other means of power transmission, meeting them upon equal terms, and

with no other consideration but that of the comparative economy with which the power is transmitted. There are many cases that are clearly cases of power transmission, or cases of work to be done at a distance from the source of power, where the question as to whether the power is to be applied continuously or intermittently may be a most important factor in the general problem. Compressed air is unique among all power transmitters—at least among long-distance power transmitters—in that it is always and instantly ready to do its work to its full capacity, and yet that it charges nothing for its services except when it is actually employed. Other transmitters may or may not propose to do the actual work a little cheaper, but they expect to be an expense to their employer for maintenance when not employed. In the pneumatic switch and signal service a single air-compressing plant is capable of operating the switches and signals upon a section of railway twenty miles long; and when the pipes are once filled with air at the required pressure, that air does not condense or suffer loss or deteriorate in any way except as it is used. Electricity makes open confession of its inability to do this intermittent work, in that while in this switch and signal service it is actually employed to give the wink to the air as to what is wanted, the air has to do the work. It need not be said that steam could not do this work, for its strength would all be turned to water before the end of the pipe was reached.

How little weight the actual power economy may have in determining the employment of compressed air for a given purpose is suggested by the conditions of the pneumatic postal service. In the cities of Europe pneumatic postal transmission has been an established commercial suc-

cess for years, and recently the same most gratifying experience is realized at the Philadelphia post-office. The application of the air is not mechanically economical, only *ten per cent* of the power employed being applied to the work of moving the carriers, while ninety per cent is "wasted" in accelerating the air and in its friction.

The "compressing-pump" of the air-brake service being now familiar to all railroad men, and being at hand or easily procurable by all railroad shops, has been of late years always ready in those shops with its supply of compressed air, and this ready supply of compressed air has led to the general employment of it in railroad shops and in railroad service for a variety of uses. Whatever it is tried for, its use for that purpose continues, and one thing leads to another. These uses of compressed air in railroad shops continually increase, not because the air is more adapted to railroad use than to any other, but because the air is there. Where the air is once used in one of these shops its use increases, the volume of air used increases, and the increasing demand for the air is met by setting up additional "compressing-pumps" in succession, until in some instances as many as eight of them have been employed together to supply a single shop. It is evident here that power economy could have little to do with the case, or some thought would be given to the economical compression of the air, and a good air-compressor would take the place of the air-brake pumps as a means of supply. This substitution is now in progress, we are happy to say, in many shops with most gratifying results.

A recent floating paragraph tells how the master mechanic of one of the railroads does his whitewashing by compressed air: "An old freight-car has been fitted with

three air-brake pumps and two reservoirs," instead of one air-compressor and one reservoir or receiver, "the pumps being driven by steam from an engine (locomotive) and a pressure of 40 pounds being maintained in the reservoirs. The car and engine are run upon the track alongside the building to be whitewashed. By a system of piping the air is carried into the building, and to the long iron nozzles used by the men in applying the fluid. Each man has an iron tube with a funnel-shaped end, from which the whitewash is sprayed upon the woodwork. To each nozzle are attached two lines of hose, one supplying the air and the other the whitewash. The air rushes into the cylinder of the nozzle, and its pressure causes a suction that brings up a stream of whitewash and at the same time expels it in the form of spray." There can be no doubt of the success of this scheme; but if it pays to use a locomotive, a freight-car, three brake-pumps, two reservoirs, and all the rest of it, for such a job, compressed air surely must be cheap at any price, or there must be economy in compressed air if economically compressed and wisely applied.

As to how much the question of power economy may have to do with the remunerative use of compressed air is suggested by an article in *Machinery*, September, 1894, describing the various uses to which compressed air is put in the West Shore R. R. shop at Frankfort, N. Y. "It is stated that the entire power cost for running the air-compressors to supply the whole shop is not more than ten cents per day, while the actual saving in labor effected is from fifteen to twenty dollars per day. In the article referred to, among the many applications of compressed air in the above shop mention is made of a machine for (by the aid of compressed air) putting the couplings into the

ends of air-brake hose. "This little machine has a record of putting together one hundred in one hour and five minutes, against twenty-five in one day by hand, and actually paid for its entire cost in one day's application."

Simply give compressed air a chance and it will quickly demonstrate its value. The progress in the use of compressed air thus far seems plainly to indicate that its wider application is promoted more by having a supply of it ready at hand, or easy to get, than by showing how cheaply it can be furnished. Those who are introducing small, cheap compressors that work with reasonable economy are doing excellent missionary work for compressed air. Farther along, as large, permanent compressing-plants are established, we may believe that the minute economies will receive the consideration which they deserve. However the air may be used, and however profitable it may be to use it, it will always be in order to get it as cheaply as possible, and economy in air-compression must always be a clear gain.

CHAPTER II.

DEFINITIONS AND GENERAL INFORMATION.

AT the beginning it would seem to be well to get together for use or reference the general facts in relation to air and to the phenomena attending its compression. As this work is intended for the greatest good of the greatest number, being for popular use, or for the use of those who will practically have to do with compressed air, and as it is in no sense for the use of expert scientists, the common standards of weight and measurement will be employed wherever it is possible to use them intelligibly. For temperatures the Fahrenheit scale will be used exclusively. All measures of length or distance will be given in feet and inches, and weights in pounds avoirdupois. Where pressures are referred to, they will be the pressures as indicated upon a common pressure gauge, or the pressures above that of the atmosphere. The absolute pressure, of course, is the gauge pressure plus the pressure of the atmosphere at the given time and place, this atmospheric pressure being usually taken as 14.7 lbs. at the sea-level. It will be necessary to refer to absolute pressures occasionally, but we trust that no misunderstanding will occur.

Air is composed of 23 parts by weight of oxygen and 77 parts by weight of nitrogen. By volume the proportions are 21 parts of oxygen and 79 parts of nitrogen. Although

oxygen is thus less than one quarter of the air, it is much more studied and written about and is apparently of much more use and importance than the larger constituent. It may be that the functions of nitrogen are not yet very fully or clearly understood. It certainly has not been considered deserving the study, nor has it received the attention that oxygen has received. Oxygen is the active partner in the combination. A friend who is blessed with more knowledge in this line than is possessed by the writer suggests that oxygen is made for the mechanic and nitrogen for the farmer.

We shall frequently use the term "free air" as we go along. The term free air in contradistinction from compressed air is only used as a matter of convenience and custom. Free air, or air at atmospheric pressure, is really compressed air, or air subjected to pressure, as truly as air at 100 lbs. pressure is compressed air, and its volume, pressure, and temperature are subject to the same laws. By free air, as the term is commonly used, is meant air at atmospheric pressure and at ordinary temperature, and it is the air as we receive it when we begin the operation of air. compression. It is free air, or it should be free air, when first admitted to the air-compressing cylinder, and it is not free air again until it is exhausted or discharged into the atmosphere, when it has done its work and we have no further use for it or connection with it.

The condition in which our free air is received is not by this general term accurately defined in any of its particulars, either as to pressure, volume, or temperature. The pressure and volume of the air may vary with the altitude or location, or with the barometric reading in any given location, or, again, the volume may vary with the tempera-

ture. The temperature may vary with the changes of the seasons or with the special surroundings. For general purposes we shall assume our free air to be at the usual sea-level atmospheric pressure of 14.7 lbs., absolute, and at a temperature of 60°.

We shall have to refer constantly to temperatures, and, as said above, the Fahrenheit scale will be used exclusively, and usually the temperatures will be the sensible temperatures, or those indicated by the common Fahrenheit thermometer, 32° being the melting-point of ice, or the point where water changes from the solid to the liquid state, and 212° being the point where it changes from the liquid to the gaseous state. The boiling-point is in practice quite a variable one, and depends entirely upon the pressure surrounding the water, 212° being the boiling-point only at ordinary atmospheric pressures near the sea-level. Water may theoretically be made to boil at any temperature above the freezing-point by sufficiently reducing the atmospheric pressure to which it is exposed. The range of the Fahrenheit scale between the melting-point of ice and the boiling-point of water is 180 degrees.

We shall have frequent occasion to refer to *absolute* temperatures. *Absolute temperature* by the Fahrenheit scale is the temperature as indicated by the thermometer plus 461 degrees. Thus at 60° by the thermometer the absolute temperature is $60 + 461 = 521$. At zero the absolute temperature is $0 + 461 = 461$. At temperatures below zero the absolute temperatures are also determined in the same way, by simple addition. Thus, if the temperature by the thermometer is 30° below zero, or $-30°$, the absolute temperature will be $-30 + 461 = 431$. In all questions relating to the volume, pressure, or weight of

air, whether compressed or not, the absolute temperature of the air has an important bearing, as the volume of the air will vary directly as the absolute temperature, and the pressure and the weight of the air will all have changing relations. If the absolute temperature of the air is increased, the volume will be increased in the same proportion, the pressure remaining unchanged. So if the absolute temperature of the air be diminished, the volume will be diminished in the same way. The relations of volume, pressure, and temperature of air are thus summarized:

1. The absolute pressure of air varies inversely as the volume when the temperature is constant.

2. The absolute pressure varies directly as the absolute temperature when the volume is constant.

3. The volume varies as the absolute temperature when the pressure is constant.

4. The product of the absolute pressure and the volume is proportional to the absolute temperature.

A cubic foot of dry air at atmospheric pressure and at any absolute temperature will weigh 39.819 lbs. divided by the absolute temperature. Thus at 60° a cubic foot of air weighs $39.819 \div (60 + 461) = .0764$ lb. So, inversely, the volume of 1 lb. of air at atmospheric pressure and at any absolute temperature may be ascertained by dividing the temperature by 39.819.

Thus at 60° as before $521 \div 39.819 = 13.084$ cu. ft.

The following table (I), from Appleton's Applied Mechanics, shows the weight and volume of air at different temperatures.

If the temperature and the pressure of air both vary the constant 2.7093 multiplied by the absolute pressure in lbs.

TABLE I.

TABLE OF THE WEIGHT AND VOLUME OF DRY AIR AT ATMOSPHERIC PRESSURE AND AT VARIOUS TEMPERATURES.

From Appleton's Applied Mechanics.

Temperature, Degrees Fahr.	Weight of One Cubic Foot in Pounds.	Volume of One Pound in Cubic Feet.
0	.0863	11.582
10	.0845	11.834
20	.0827	12.085
30	.0811	12.336
32	.0807	12.386
40	.0794	12.587
50	.0779	12.838
60	.0764	13.089
70	.0750	13.340
80	.0736	13.592
90	.0722	13.843
100	.0710	14.094
110	.0697	14.345
120	.0685	14.596
130	.0674	14.847
140	.0662	15.098
150	.0651	15.350
160	.0641	15.601
170	.0631	15.852
180	.0621	16.103
190	.0612	16.354
200	.0602	16.605
210	.0593	16.856
212	.0591	16.907

per sq. in. and divided by the absolute temperature will give the weight of a cubic foot.

What will be the weight of 1 cu. ft. of air at 60 lbs. pressure and 100° temperature?

$$2.7093 \times (60 + 14.7) \div (100 + 461) = .3607 \text{ lb.}$$

The volume of 1 pound of air may be obtained by dividing the absolute temperature by the absolute pressure and dividing this by the same constant, 2.7093.

What will be the volume of 1 lb. of air at 75° temperature and 50 lbs. pressure?

$$(75 + 461) \div (50 + 14.7) \div 2.7093 = 3.052 \text{ lbs.}$$

If the temperature of the air is changed from one absolute temperature T to another absolute temperature t, the volume remaining constant, the resulting absolute pressure p may be obtained from the original absolute pressure P by the simple proportion $T : t :: P : p$, or $\frac{P \times t}{T} = p$.

It is not supposed that heat is an actual existence any more than sound or light is; still it is very necessary, especially in all matters relating to compressed air, to be able to accurately measure and state the effects of heat, and to have some unit or standard of measurement and comparison. The unit of heat generally adopted is that quantity of heat that will raise the temperature of one pound of water one degree. One unit of heat if applied to one pound of anything else will not have precisely the same effect in raising the temperature that it has when applied to water. More heat is required to raise the temperature of one pound of water one degree than is required for any other substance. The heating effect of a unit of heat applied to different substances is found to vary widely, and the special quantity of heat required to raise the temperature of one pound of any substance one degree is known as its specific heat. The specific heat of water being 1, the specific heat of air is .2377, or the same unit of heat that would raise the temperature of one pound of water one degree would raise the temperature of one pound of air more than four degrees. The application of heat to air or to any elastic fluid may have either of two effects. It may

increase the volume while the pressure remains constant, or it may increase the pressure while the volume remains constant. The specific heat will be quite different in the two cases. The specific heat of air—.2377, as given above—is its specific heat at constant pressure, and the heat applied in this case exhibits its effect in increasing the volume of the air. If the air be confined so that there can be no increase of volume, its specific heat is only .1688, or about one sixth that of water. Heat applied to air at constant volume increases the pressure of the air. If heat be applied to air under constant pressure, raising its temperature from 32° to 212°, the increase in volume will be from 1 to 1.367; and if heat be applied to air at constant volume, raising its temperature, as before, from 32° to 212°, the increase in absolute pressure will be from 1 to 1.365, the numerical result being practically alike in the two cases, but the heat expended will be as .2377 : .1688, or nearly one half more in one case than in the other.

When air is compressed, or when its volume is reduced by the application of force, the temperature of the air is raised. This phenomenon occurs entirely regardless of the time employed in the compression. If during the compression the air neither loses nor gains any heat by communication with any other body, the heat generated by the act of compression remaining in the air and increasing its temperature, then the air is said to be compressed adiabatically, and such compression is adiabatic compression. When the pressure is removed from the air and it is allowed to expand, its temperature falls, and if the air during this operation receives no heat from without, it is said to expand adiabatically. Adiabatic compression or expansion of air is compression or expansion without loss or gain of heat by

the air. This expression "without loss or gain of heat," it will be noticed, does not mean maintaining a constant temperature, but precisely the reverse of that.

If during compression the air could be kept at a constant temperature by the abstraction of the heat as fast as it was generated, the air would then be said to be compressed isothermally. In isothermal compression or expansion the air remains at a constant temperature throughout the operation.

The rate of increase in the temperature of air during compression is never uniform. The temperature rises faster during the earlier stages of the compression than when the higher pressures are reached. Thus in compressing from 1 atmosphere to 2 atmospheres the increase of temperature will be greater than in compressing from 2 to 3 atmospheres, and so on. The rate of increase of temperature also varies with the initial temperature. The higher the initial temperature the greater will be the rate of increase at any point and throughout the compression.

Attention is called to the diagram which appears as a frontispiece to this work. It is taken from "Compressed-Air Production," by W. L. Saunders, C.E. The writer hereof is in the habit of keeping this diagram in sight, and finds it suggestive and handy in the off-hand solution of many questions that arise. It would seem to be worthy of a rather fuller explanation than Mr. Saunders has favored us with. The diagram in fact comprises two distinct diagrams, the one showing the temperature of the air, and the other showing the volume of the air at different stages of compression. If the diagrams are understood, there is no danger of confusing the one with the other, and as many of the lines do service for both diagrams, we are able to get

much from a small space. Compression is supposed to commence at the left of the diagram with any given volume of air at atmospheric pressure. As the compression proceeds the successive stages of pressure are indicated by the series of vertical lines. Beginning at the extreme left with the gauge pressure at zero, 0, as shown at the bottom of the diagram, or with an absolute pressure of 1 atmosphere, as indicated at the top of the diagram, when the first vertical line is reached the air is then compressed to 2 atmospheres, as shown by the figure at the top, or to 14.7 lbs. gauge pressure, as shown by the figures at the bottom. When the next vertical line is reached, the air has been compressed to 3 atmospheres, absolute, or to 29.4 lbs. gauge pressure, and so on, the diagram extending to 21 atmospheres, or 294 lbs. gauge pressure at the extreme right.

In connection with the compression of air the important facts to be known are the temperature of the air when any given pressure is reached, and also the relative volume of the air when compressed to any given pressure, and these points it is the function of the diagram to show. The curved lines running from the lower left-hand corner *A* of the diagram are the lines of temperature, and they indicate by their height above the base-line *AB* the temperature of the air at any stage of the compression. It is assumed in the use of this part of the diagram that the air is compressed adiabatically, or that it loses none of the heat of compression during the operation. The several horizontal lines of the diagram serve to indicate by their height above the base-line *AB* the temperature attained. The space between any two adjacent horizontal lines represents 100° of temperature. Thus the temperature at the base-line

AB being zero the temperature at the first line above it is 100°, and so on. The temperatures indicated by the lines are shown by the figures at the left of the diagram along the vertical starting-line *AC*. Intermediate temperatures falling between the lines may be estimated by the relative distances from the lines. The temperature of the air at any stage of the compression depends upon its initial temperature. The higher the initial temperature is the higher will be the temperature throughout the compression. The diagram gives temperature-lines for the compression of air from the several initial temperatures of 0°, 60°, and 100°. These lines show, as noted above, that the higher the initial temperature the more rapid is the rise throughout the compression. Thus comparing the compression-line from 0° with the line of compression from 100° we notice that when the air has been compressed from 1 atmosphere to 10 atmospheres the original difference of 100 degrees has become 200 degrees, and when the compression is carried to 20 atmospheres, the difference has become 250 degrees.

The curved lines starting downward from the point *C* at the upper left-hand corner of the diagram represent the volume of any unit of air after compression to any given pressure. The upper curved line represents the resulting volume after compression without any cooling of the air during compression, or with all the heat of compression remaining in the air. This is the adiabatic compression-line. The lower or inner of the two curved lines represents the volume of air after compression to any given pressure, and with all the heat of compression abstracted immediately as it is developed, or with the air constant at the initial temperature throughout the compression. This

is the line of isothermal compression. The initial temperature of the air whether it is compressed isothermally or adiabatically is not a factor in determining the resulting volume. The total height of the starting-line *AC* representing 1 volume of air, the volume at any stage of the compression is represented by the vertical height of either curved line at that point. The several horizontal lines of the diagram serve to indicate the height, and by the height the volume, of the air at any pressure, and in this relation the lines have an entirely different function from that borne by them in relation to the lines of temperature. The initial volume is assumed to be divided into ten equal parts, and the space between any two adjacent horizontal lines represents one tenth of the original volume. Thus the first horizontal line below the top line *CD* represents nine tenths of the initial volume, the next line below indicates eight tenths of the original volume, and so on. These values are indicated by figures at the right of the diagram along the line *DB*.

TABLE II.

TABLE OF VOLUMES, MEAN PRESSURES, TEMPERATURES, ETC., IN THE OPERATION OF AIR-COMPRESSION FROM 1 ATMOSPHERE AND 60° FAHR.

1	2	3	4	5	6	7	8	9	10	11
Gauge Pressure.	Absolute Pressure.	Pressure in Atmospheres.	Volume with Air at Constant Temperature.	Volume with Air not Cooled.	Mean Pressure per Stroke. Air Constant Temperature.	Mean Pressure per Stroke. Air not Cooled.	Mean Pressure during Compression only. Air Constant Temperature.	Mean Pressure during Compression only. Air not Cooled.	Final Temperatures. Air not Cooled.	Gauge Pressure.
0	14.7	1	1	1	0	0	0	0	60	0
1	15.7	1.068	.9363	.95	.96	.975	.43	.44	71	1
2	16.7	1.136	.8803	.91	1.87	1.91	.95	.96	80.4	2
3	17.7	1.204	.8305	.876	2.72	2.8	1.4	1.41	88.9	3
4	18.7	1.272	.7861	.84	3.53	3.67	1.84	1.86	98	4
5	19.7	1.34	.7462	.81	4.3	4.5	2.22	2.26	106	5
10	24.7	1.68	.5952	.69	7.62	8.27	4.14	4.26	145	10
15	29.7	2.02	.495	.606	10.33	11.51	5.77	5.99	178	15
20	34.7	2.36	.4237	.543	12.62	14.4	7.2	7.58	207	20
25	39.7	2.7	.3703	.494	14.59	17.01	8.49	9.05	234	25
30	44.7	3.04	.3289	.4638	16.34	19.4	9.66	10.39	255	30
35	49.7	3.381	.2957	.42	17.92	21.6	10.72	11.59	281	35
40	54.7	3.721	.2687	.393	19.32	23.66	11.7	12.8	302	40
45	59.7	4.061	.2462	.37	20.52	25.59	12.62	13.95	321	45
50	64.7	4.401	.2272	.35	21.79	27.39	13.48	15.05	339	50
55	69.7	4.741	.2109	.331	22.77	29.11	14.3	15.98	357	55
60	74.7	5.081	.1968	.3144	23.84	30.75	15.05	16.89	375	60
65	79.7	5.423	.1844	.301	24.77	31.69	15.76	17.88	389	65
70	84.7	5.762	.1735	.288	26	33.73	16.43	18.74	405	70
75	89.7	6.102	.1639	.276	26.65	35.23	17.09	19.54	420	75
80	94.7	6.442	.1552	.267	27.33	36.6	17.7	20.5	432	80
85	99.7	6.782	.1474	.2566	28.05	37.94	18.3	21.22	447	85
90	104.7	7.122	.1404	.248	28.78	39.18	18.87	22	459	90
95	109.7	7.462	.134	.24	29.53	40.4	19.4	22.77	472	95
100	114.7	7.802	.1281	.232	30.07	41.6	19.92	23.43	485	100
105	119.7	8.142	.1228	.2254	30.81	42.78	20.43	24.17	496	105
110	124.7	8.483	.1178	.2189	31.39	43.91	20.9	24.85	507	110
115	129.7	8.823	.1133	.2129	31.98	44.98	21.39	25.54	518	115
120	134.7	9.163	.1091	.2073	32.54	46.04	21.84	26.2	529	120
125	139.7	9.503	.1052	.202	33.07	47.06	22.26	26.81	540	125
130	144.7	9.843	.1015	.1969	33.57	48.1	22.69	27.42	550	130
135	149.7	10.183	.0981	.1922	34.05	49.1	23.08	28.05	560	135
140	154.7	10.523	.095	.1878	34.57	50.02	23.41	28.66	570	140
145	159.7	10.864	.0921	.1837	35.09	51	23.97	29.26	580	145
150	164.7	11.204	.0892	.1796	35.48	51.89	24.28	29.82	589	150
160	174.7	11.88	.0841	.1722	36.29	53.65	24.97	30.91	607	160
170	184.7	12.56	.0796	.1657	37.2	55.39	25.71	32.03	624	170
180	194.7	13.24	.0755	.1595	37.96	57.01	26.36	33.04	640	180
190	204.7	13.92	.0718	.154	38.68	58.57	27.02	34.06	657	190
200	214.7	14.6	.0685	.149	39.42	60.14	27.71	35.02	672	200

CHAPTER III.

A TABLE FOR AIR-COMPRESSION COMPUTATIONS.

THE accompanying Table II, which the writer uses constantly in his own practice, will be found convenient for working up indicator diagrams from air-compressing cylinders, and in general computations relating to air-compression. It should require little explanation. Throughout the table the air is assumed to be compressed from the normal pressure of 1 atmosphere,—14.7 pounds,—and from an initial temperature of 60° Fahrenheit. The first three columns of the table are of course different forms of the same thing—the pressure to which the air is compressed. The last column of the table is also the same as the first merely for the convenience of following the lines of figures. The first column gives the pressures as they would actually be shown by a steam- or pressure-gauge. It would be the actual available working pressure of the air after compression. The second column, or the absolute pressure, is obtained by adding the normal atmospheric pressure—14.7 pounds—to the gauge pressure. The third column, showing the pressure in atmospheres, is obtained by dividing the absolute pressure by the normal atmospheric pressure —14.7 pounds.

Column 4 gives the volume of air (the initial volume being 1) after isothermal compression to the given press-

ure; that is, assuming that the temperature of the air has not been allowed to rise during the compression, or that, if the air has not been completely cooled during the compression, it has been cooled to the initial temperature after the compression. In this case the volume is assumed to be inversely as the absolute pressure, which is very nearly correct. The figures in column 4 are in fact reciprocals of those in column 3, and they are obtained by dividing 1 by the several successive values in column 3. Thus, for a gauge pressure of 50 pounds, the volume by isothermal compression should be $1 \div 4.401 = .2272$, as given in column 4. So far as the air-compressor is concerned, this column represents an eternally unattainable ideal. There is, and as far as we can see there can be, no absolutely isothermal compression. Some "hydraulic" compressors are claimed to accomplish it, but while there is no promise of their practical success thy have no right to stand in evidence. The compressed volume while in the compressing cylinder, or at the moment of discharge, will always be greater than given in column 4 for the corresponding pressure, because it is impossible to compress air and at the same time abstract all the heat of compression from it. This column does, however, give the volume of air that will be realized if the air is transmitted to some distance from the compressor, or if it is allowed to give up its heat in any way before it is used. Air will be found to lose its heat very rapidly, and this column may be taken to represent the volume of air after compression actually available for the purpose for which the air may have been compressed.

Column 5 of the table gives the volume of air at the completion of the compression, assuming that the air has

neither lost nor gained any heat during the compression, and that all the heat developed by the compression remains in the air. This column shows the air more nearly as the compressor usually has to deal with it, although the condition represented by this column—adiabatic compression—is never actually realized, any more than isothermal compression is realized. In any compressor the air will lose some of its heat during the compression, and the air is never as hot during the compression, nor at the completion of the compression, as theory says that it should be. The theory is all right, but the air loses some of its heat. The slower the compressor runs the better chance the air has to give up some of its heat, and consequently the smaller will be its volume all through the operation, and the less will be the power required. High or excessive speeds are not in the interest of economy for many reasons. If the cylinder and the cylinder-heads are water-jacketed, the cooling of the air and the reduction of volume and of mean effective resistance will be quite appreciable ; but in general practice the actual volumes of air at the completion of compression will be found to be nearer the figures given in column 5 than to those in column 4.

Column 6 gives the mean effective resistance to be overcome by the air-cylinder piston in the stroke of compression, assuming that the air throughout the operation remains constantly at its initial temperature—isothermal compression. Of course the air never will remain at constant temperature during compression, and this column remains the ideal to be kept in view and striven for and continually approximated in economical compression.

Column 7 gives the mean effective resistance to be over-

come by the piston for the compression stroke, supposing that there is no cooling of the air during the compression—adiabatic compression. As we have seen, there is more or less—generally less, but always some—cooling of the air during its compression, so that the actual mean effective resistance will always be somewhat less than as given in this column ; but for computing the actual power required for operating air-compressor cylinders the figures in this column for the given terminal pressures may be taken and a certain percentage added for friction,—say 5 per cent, —and the result will represent very closely the power required by the compressor. In proposing to add 5 per cent for friction we do not mean that the total friction of a steam-actuated air-compressor will be only 5 per cent, for it will probably be more than 10 per cent, but part of this 10 per cent will have been compensated for by the partial cooling of the air during the compression. In some compressors now in use it is probable that so much cooling is effected during the compression, and so much power is saved thereby, as to entirely compensate for the friction of the machine, and nothing need be added to the result. The values given in columns 6 and 7 are of course used in computing the horse-power of an air-compressing cylinder precisely as the mean effective pressure per stroke in a steam-cylinder is used in computing its power. In the steam-cylinder the computation gives the power developed by the steam, and the same system of computation applied to the air-cylinder gives the power used in the compression.

Having an air-compressing cylinder 20″ dia. × 2′ stroke at 75 revolutions per minute, or 300′ piston speed, com-

pressing air adiabatically to 75 lbs., the horse-power used will be computed as follows:

$$20^2 \times .7854 \times 35.23 \times 300 \div 33{,}000 = 100 \text{ H.-P.}$$

It may be proper to suggest here one caution as to the use of the mean effective pressures given in columns 6 and 7. The pressures given being for compression to different pressures from an initial pressure of 1 atmosphere, it does not follow that those values will be correct for computations in compound compression, or for compression from any other initial pressure but that of 1 atmosphere. Thus in column 7 the M.E.P. for compressing from 1 atmosphere to 50 lbs. gauge pressure is 27.39. In this case the pressure of the air compressed is increased 50 lbs., but it does not follow that we can take air at 50 lbs. and compress it to 100 lbs. with the same mean effective pressure. In the latter case the M.E.P. required would be 40.33, or 47 per cent greater than in the former case.

Column 8 gives the mean effective resistance for the compression part only of the stroke in compressing air isothermally from a pressure of 1 atmosphere to any given pressure. This at once calls our attention to the two distinct operations involved in practical air-compression: the actual compression of the air to the given pressure, and the delivery or expulsion of the air from the cylinder after the full pressure is attained. These two operations correspond inversely to the two operations occurring in the cylinder of a steam-engine: the admission of the steam, where it is sustained at approximately full pressure until the point of cut off, and the expansion of the steam from the point of cut off to the termination of the stroke, the expansion period in the steam-cylinder of course corre-

sponding inversely with the compression in the air-cylinder, and the admission of the steam corresponding with the delivery of the air.

It will be noticed that the mean effective pressures in columns 8 and 9, for the compression part only of the stroke, are much lower than those in columns 6 and 7 for the whole stroke, but when to the work of the compression part of the stroke is added the work of delivery, the values will be found to correspond very nearly. Thus when compressing adiabatically to 50 pounds gauge pressure the volume of air delivered will be (column 5) .35 of the original volume, or .35 of the stroke for each cylinderful of free air, sot hat the pressure or resistance for .35 of the stroke will be 50 lbs., while for the compression part of the stroke—$1 - .35 = .65$—the resistance will be 15.05, as given in column 9. Then $(15.05 \times .65) + (50 \times .35) = 27.28$, which corresponds as well as could be expected with the value in column 7 for the whole stroke—27.39.

There is also to be observed a less proportional difference between the values in columns 8 and 9 than between those in columns 6 and 7, but this also will be found to be compensated for by the differences in terminal volume for isothermal or for adiabatic compression and the different proportion of the stroke occupied by the full pressure of delivery. Thus comparing the figures for isothermal compression with those just given for adiabatic compression, compressing to 50 lbs. as before, we have : $(13.48 \times .7728) + (50 \times .2272) = 21.78$, a result which may be said to be identical with the value 21.79 for the whole stroke, as given in column 6.

Columns 8 and 9, as will be referred to later, will be found serviceable in computing the power used in the first

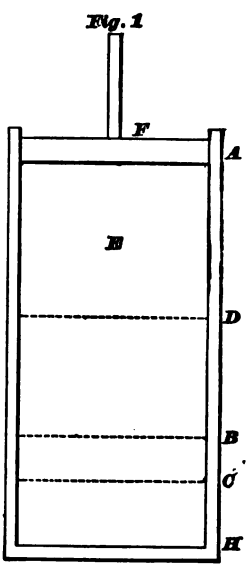
stage of compound compression, where generally the entire function of the first cylinder is that of compression only, its total contents from the beginning to the end of the stroke being simply compressed into the volume contained in the smaller cylinder, and there being no part of the stroke properly occupied in delivery or expulsion at any completed pressure.

Column 10 gives the theoretical temperature of the air after compression, adiabatic, to the given pressure. As we have remarked elsewhere, the actually observed temperature in these cases is never as high as the theoretical temperature. This is not that the theory is incorrect, for, as usual, the theory is more nearly correct than "practical" people are wont to allow. If the temperature of the compressed air by observation is not found to correspond with the figures as given, it is only because the air is being cooled by conduction or radiation even while it is being heated by compression.

CHAPTER IV.

THE COMPRESSED-AIR PROBLEM.

THE general problem of air-compression and of the application of compressed air to the re-development of power may be stated in simple terms. Fig. 1 really tells the whole story. The piston *F* is fitted to the cylinder *E*, so that we may assume it to move freely and without leakage. The piston being at *A*, as shown, and the cylinder being filled with air at a pressure of 1 atmosphere, and at normal temperature, a sufficient weight is placed upon the piston to force it down into the cylinder and compress the air contained in it to a pressure of, say, 6 atmospheres. The volume being inversely as the pressure, the piston should go down to *C*. We find, however, that it actually only goes down to *B*, and the reason is that while the air is being compressed the operation of compression also heats it, and the heat distends or expands the air, and its volume is consequently considerably greater than it should be, upon the assumption that the volume is always inversely as the pressure.



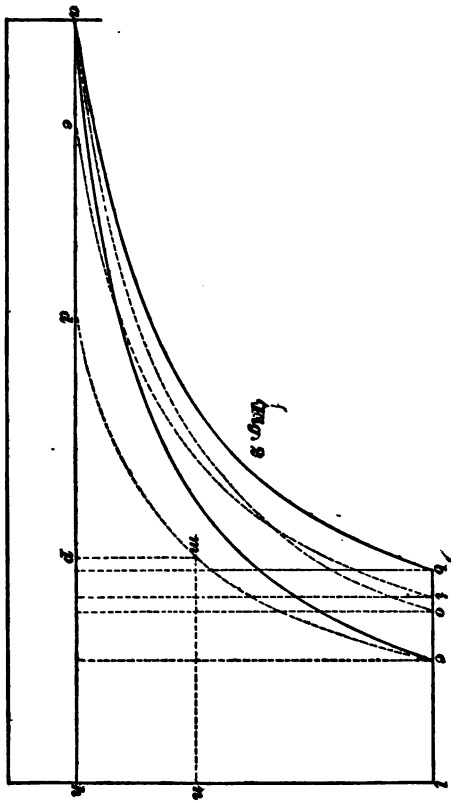
This is an illustration of the frequent differences that arise between theory and practice, with the usual result that practice is all right, and that theory will be in perfect accord with it when the theory in the case is complete. Theory thus far had not thought of the temperature of the air.

Supposing both the piston and the cylinder to be absolute non-conductors of heat, and that the air heated by the compression loses none of its heat of compression, then if the weight which forced the piston down to *B* be taken away, the piston will be driven back to its original position at *A*, and the air contained in the cylinder will have resumed its normal pressure and temperature, and will have done as much work, or will have exerted as much force, by its return, as was employed in the act of compression. If while the piston was at *B*, and with the weight upon it sufficient to balance the pressure of 6 atmospheres, the air by any means had been cooled to its original temperature, the piston would have fallen to *C*, and the law that the volume varies inversely as the pressure would have held good, for then the initial and the final temperatures would have been the same. The air being thus cooled to its original temperature, and the piston being at *C*, upon removing the weight from the piston it would return only to *D*, instead of to *A*. When the piston arrived at *D*, the pressure of the air in the cylinder would have fallen to the original pressure of 1 atmosphere, and the piston at *D* would be balanced between the pressures above and below it. As the air is heated in the operation of compression, so is it correspondingly cooled during its expansion, and when the piston reaches *D* the air in the cylinder is then at atmospheric pressure, because it is then much colder than it was at the

beginning; and it is solely because of this loss of heat that the pressure falls so early, and that the piston does not return to *A* where it started from. If while the piston is at *D* the air can by any means recover all the heat which it has lost, the piston will return to *A* as before. The distance *DA* compared with *CA*, or the distance *DC*, represents the total possible theoretical loss of power in the compression and the re-expansion of air.

At the risk of anticipating a number of points that I hope to bring out more fully and in detail later on, we may now refer to the more or less practical diagram Fig. 2. This diagram, scale 40, is intended to show the practical possibilities in the use of compressed air at 75 lbs. gauge, or 6 atmospheres. The line *ab* is the adiabatic compression-line, or the line of compression, upon the assumption that no heat is taken away from or is lost by the air during the compression. The initial temperature of the air being 60 degrees, the final temperature would be about 415 degrees, and the final volume would be .28 of the original volume. The line *ac* is the isothermal compression-line, which assumes that all the heat of compression is got rid of just when it is produced, or that the air throughout the compression remains constantly at its initial temperature. The final volume in this case is .1666 of the original volume. Remembering that these lines, *ab* and *ac*, represent the compression of the same initial volume of air, it is evident that there is quite a difference in the amount of power employed in the two cases, and herein lies the loss, or the possibility of loss, of power in the operation of compression. The mean effective pressure or resistance of the air for the stroke upon the adiabatic line *abl* is 35.36 lbs., while the mean effective pressure for the isothermal compression-line

acl is but 27 lbs., or only 76 per cent of the former. The comparison should, however, be reversed. The adiabatic



mean effective pressure is 131 per cent of the isothermal mean effective pressure:

$$27 : 35.36 :: 1 : 1.31,$$

and this 31 per cent is, of course, the additional, or, as we might say, the unnecessary, power employed, assuming iso-

thermal compression to be attainable. Neither of these compression-lines, *ab* or *ac*, is possible in practice. Air cannot be compressed without losing some of its heat during compression, so that the actual compression-line must always fall within or below the line *ab*. On the other hand, it is equally impossible to abstract all the heat from the air coincidently with the appearance of that heat, so that the actual compression-line must always fall outside or above the line *ac*. The best air-compressor practice of to-day is very near the line *ao*, or the mean of the adiabatic and the isothermal curves. The actual line is generally above this, and seldom below it. It would be impossible to produce a line exactly coincident with this in practice. If we produced a line giving the same mean effective pressure as *ao*, it would probably run above *ao* for the first half of the stroke, and perhaps a little below it at the last. If the compression were two-stage or compound,—that is, if it were done in two or more cylinders instead of in one,—there would of course be breaks in the continuity of the compression-curve. The mean effective pressure for the line *aol* is about 31.5 lbs., or still nearly 17 per cent in excess of the M.E.P. for the line *acl*. As *aol* represents exceptionally good practice, the loss of power for the average practice in air-compression, independently of the friction of the machinery, may be put at 20 per cent. Lest some impatient ones should drop the subject here, or lest some rival of compressed air should pick up this and run away with it, we might insert a reminder here that all this loss is not necessarily final. In all these comparisons for efficiency the actual compression-line is always to be compared with the isothermal line *acl*, because that is the ideal line for compression without loss of power, and because the termi-

nal volume *cl* is the volume actually available for use, no matter how economically or wastefully the air may have been compressed. Though at the completion of the compression stroke there is always some of the heat of compression remaining in the air, and its volume is always greater than *cl*, that heat is always lost in the transmission of the air, or in its storage, and the available volume is never practically above *cl*.

After the cooling and contraction of the compressed air comes the question of loss in the transmission of it. To cause the air to flow through the pipe there must be some excess of pressure at the first end of it, a constant decrease of pressure as the air advances, and consequently a loss of available power at the delivery end. But this loss has been greatly exaggerated. Here, as in other matters, the air-compressor builders have—unwittingly, we will say—done more harm than good as regards the interests of compressed air. Formidable tables are in all the air-compressor catalogues, showing the loss of pressure due to the friction of air in pipes. The tables are not dangerous, and are not published primarily for the purpose of frightening timid investors. They are only intended to suggest the size of pipe most suitable for any given case of transmission. If they tell us truly of the loss of pressure, they still fail to tell us that the loss of pressure is not necessarily, or to the same extent, a loss of power. The actual truth is that there is very little loss of power through the transmission of compressed air in suitable pipes to a reasonable distance, and the reasonable distance is not a short one. With pipes of proper size, and in good condition, air may be transmitted, say, ten miles, with a loss of pressure of less than 1 lb. per mile. If the air were at 80 lbs. gauge, or 95 lbs. absolute, upon entering

the pipe, and 70 lbs. gauge, or 85 lbs. absolute, at the other end, there would be a loss of a little more than 10 per cent in absolute pressure, but at the same time there would be an increase of volume of 11 per cent to compensate for the loss of pressure, and the loss of available power would be less than 3 per cent. With higher pressures still more favorable results could be shown.

Having compressed the air and conveyed it to the point where we wish to use it, we may turn again to Fig. 2, and see what we will be able to do with the air. The air may be used in various ways with widely different economic results, and little ingenuity is required to accomplish enormous losses. Having the volume *cl*, and using it in a cylinder of suitable capacity, cutting off so as to expand down to 1 atmosphere before release, the adiabatic expansion-line, or the lowest line that the air could make, would be the line *cd*, and the total loss in the use of the air, as compared with the power cost of compressing it, would be the difference between the areas *aolh* and *lcdh*, the latter being 66 per cent of the former.

The temperature of the air at *c*, where the expansion begins, being assumed to be 60°, the cooling of the air which always accompanies its expansion will bring the temperature far down the scale when *d* is reached, *d* being, of course, the end of the cylinder wherein the expansion takes place. The theoretical temperature of the air at the end of the stroke would be about − 150°. The actual temperature in these cases is never found as low as the theoretical temperature, because the air receives heat from the cylinder and from the walls of the passages with which it comes in contact; but it is usually still cold enough to cause serious inconvenience in practice, and this cooling of the air

may in many cases be fatal to its employment, entirely regardless of the economy of the case. The air almost invariably contains moisture, the amount varying with the surrounding meteorological conditions, and as the air becomes attenuated and so intensely cold the water is rapidly frozen in the passages, and soon chokes them up and stops the operation of the motor. The prevention or the circumvention of the freezing up of air apparatus is an additional complication of the compressed-air problem to be considered later.

The trouble from the freezing up naturally suggests the heating of the air before it is used. The heating or reheating of the air, where it is practised, not only brings us out of our trouble about the freezing up, but it increases the volume of the air and its consequent available power at a very slight expense for the heating. If the volume of air *cl*, being now at 60°, be passed through a suitable heater and its temperature raised to 300°, its volume will then be *il*, instead of *cl*, or .2434 instead of .1666, an increase of volume of about 50 per cent. In practice, to insure a temperature of 300° in the cylinder at the beginning of the expansion, it will be necessary to heat the air considerably above that temperature, say to 400°, as the air loses its heat very rapidly. If now we use this reheated air, the volume *cl* then becoming *il*, and expanding this air down to *e*, supposing the temperature at *i* to be 300°, the theoretical final temperature will be about zero. The actual temperature, it is pretty certain, will not be below the freezing-point, and all our trouble about the freezing of the passages will have disappeared, and the power realized will have been much increased. It seems to be quite practicable, by effective cooling of the air during its compression, and by

reheating it before its re-expansion, to bring the expansion-line *ie* to enclose an area not less than that enclosed by the compression-line *ao*, and then the entire losses will be those attributable to the clearances and to friction. It is said that in practice 85 per cent of the initial power has already been realized after transmitting the air to considerable distances. "It is said" accomplishes many wonderful feats.

It was remarked above that the air after compression and transmission might be employed with widely different economic results. As an instance of "how not to do it" I might cite the case, of too frequent occurrence, where air is delivered to a mine for operating rock drills and other mining machinery, and air then taken from the same pipe-line for operating a pump. This practice would be all right if the pump were adapted to the work to be done and to the pressure of air carried. The pump, however, is generally a common direct-acting steam-pump, with all that the term implies, and which has been obtained without any reference to the economical use of the air. As it has probably already been run by steam, or is designed to be run by steam, it calls for a low operating pressure; this being a necessity on account of the condensation and loss of pressure in steam when transmitted through long pipes. Say that the compressed-air pipe carries 75 lbs. pressure, while the pump only requires 25 lbs. It would be an advantage in a case like this to use a pressure-reducer in the supply-pipe at a considerable distance from the pump, so that the expansion to the lower pressure required might take place, and the air have an opportunity to recover its temperature and volume before going into the pump. This, however, is seldom attended to, and the required reduction of pressure is effected entirely by the throttle-valve at the instant of admission. The available power,

then, when the air is so employed, will be represented by the area *pmnh* as compared with the area *ablh*, or, at the best, *aolh*, representing the power that was expended in compressing the air. Then, if we deduct the losses attributable to the useless filling of the large clearances of the common steam-pump, and to the leakages that are the usual accompaniment of such generally extravagant practices, it is little wonder that compressed air is held in low esteem. Under circumstances far from the most unfavorable I have found pumps realizing only 15 per cent of the power expended at the compressor, and I have no doubt that there are many pumps being operated, or whose operation is attempted, where not more than 10 per cent of the original power is realized; and, even then, when the use of compressed air for operating such pumps under such conditions is condemned, it is apt to be because they freeze up and won't go, rather than on account of their enormous waste of power. From the fact that a mining pump has a lift that is nearly constant, the pump, if properly proportioned and adapted to its work, should be an efficient missionary for compressed air, rather than its most malignant traducer.

The word "loss" that we find ourselves using in connection with this general subject should not be allowed to mislead us. The use of compressed air is for the accomplishment of a desirable purpose, and it is not to be expected that such a purpose can be effected for nothing. The transmission of power is as much to be paid for as the generation of the power. Where water power is used, the means of transmission may be the principal item of cost. Where the difference between the power expended and the power realized is not excessive, that difference is simply a fair price paid for a good service rendered, and there is no

loss about it. Where losses do occur in the use of compressed air, they are like the losses which occur in business, and which cut short many a brilliant career. Power is lost simply because it is not saved, and the means of saving are not hard to find nor far to seek. The excessive losses are not necessary nor unavoidable, nor without compensation. A failure to understand and appreciate this situation impedes the progress of compressed air.

TABLE III.

TABLE OF FINAL TEMPERATURES OF AIR COMPRESSED ADIABATICALLY TO DIFFERENT GAUGE PRESSURES FROM AN INITIAL PRESSURE OF 1 ATMOSPHERE, AND FROM DIFFERENT INITIAL TEMPERATURES.

Final Pressure Gauge.	Initial Temp. 0°.	Initial Temp. 32°.	Initial Temp. 60°.	Initial Temp. 100°.
1	8	41	70	111
2	16	50	79	121
3	25	59	88	132
4	33	67	97	140
5	41	75	106	150
10	74	113	144	191
15	104	144	177	226
20	130	171	207	258
25	153	196	233	287
30	175	219	258	313
35	195	240	280	337
40	213	260	301	360
45	231	279	321	381
50	247	296	339	401
55	262	316	357	420
60	277	328	373	437
65	291	343	389	454
70	304	358	404	471
75	317	371	419	486
80	330	384	433	501
85	342	397	446	516
90	353	410	459	530
95	364	422	472	543
100	375	435	484	556
125	425	486	540	617
150	468	532	588	669
175	507	574	633	717
200	542	612	672	781

CHAPTER V.

THE INDICATOR ON THE AIR-COMPRESSOR.

READING AND COMPUTING THE DIAGRAM.

THE recent advances that have been made in steam-engine economy are not fully and generally realized. The engines of the Great Eastern steamship of forty years ago, representing the best engineering practice of her day, developed 8000 horse-power. The engines of the Campania to-day show 30,000 horse-power upon practically the same consumption of coal. The gain is attributable to the adoption of the multiple expansion-engine, to the reheating between the steps, and to the general prevention of condensation; but the promoter and adviser all along the way through the successive stages of improvement has been the indicator. The indicator is to-day the companion and the trusted monitor of the steam-engine designer and builder as well as of the engineer. He would be a strange competitor for steam-engine trade in these days who would not freely and gladly show the cards from his engine, and it goes without saying that he would be an unsuccessful one. The air-compressor business is still an "infant industry," although a growing one. No better evidence is needed of the juvenility of the air-compressor trade of to-day than the difficulty of obtaining cards from most of the

"standard" compressors. And yet the services of the indicator may be as valuable to the air-compressor and the air-engine as to the steam-engine, and they are certainly fully as applicable.

All circumstances seem peculiarly to invite the application of the indicator to the air-compressor, and to the study of air-compression practice and results by its aid. In fact, the air-compressor seems to be the ideal and only perfect field for the indicator. So far as I know, a steam-actuated air-compressor is the only machine where an indicator can be applied and be made to tell the whole story of the power developed and of the work done. In the steam-pump the report of the card of the water-cylinder is affected by questions relating to the inertia of the body of water. With a steam-engine of any type there is always some uncertainty about the friction of the working parts of the engine. We can take what we are pleased to call the "friction diagram," when the engine is running without doing any external work, and we know what resistance the steam has to overcome at that time; but that tells us comparatively little of the resistance of the engine parts when loaded. We know that the friction of nearly every working part of the engine increases with the load, but when the load is on, we do not know from the indicator-card how much of its mean effective indicates actual work done or how much of it belongs to the friction of the engine, and to get the result with any certainty and accuracy it is necessary to employ some form of dynamometer in connection with the indicator, and let them fight it out between them. In the case of the air-compressor this is all different. The air-compressor is its own dynamometer. By taking cards from both the air- and the steam-cylinders at the same

time, or when the compressor is running under the same conditions, we get a perfect statement of the power developed and of the actual work done, and then we know too that the difference in indicated horse-power between the air- and the steam-cards clearly shows the power that has been expended merely to keep the machine in motion. The cards not only give the comparative total power and work, but also the relations of the one to the other at any point of the stroke, showing the air resistance at any point, as well as the force of the steam at the same point, and through this knowledge it will advise us whether the air is compressed with economy or whether better results are to be sought for.

Realizing the importance of the indicator as an indispensable aid in the full development of economical air-compression, it is proper that we learn what we can of the peculiarities of the air-card and of the means of manipulating and interpreting it. We can only consider at first the card from the single air-cylinder, in which the whole operation of air-compression is completed at a single stroke. The cards from cylinders in which either stage of a compound compression is carried on assume peculiar shapes, which we may find pleasure in studying later on.

To an indicator-man who has been brought up, as most have, exclusively upon steam-cards the air-card is at first a little confusing, from the fact that all the operations upon the one card are the reverse of those upon the other. The admission-line of the steam-card is the delivery-line of the air-card ; the expansion-line in the one is the compression-line in the other ; the exhaust or back-pressure line is the admission-line, and the compression-line becomes the re-expansion-line. One can, however, soon "catch on" and

become familiar with each operation and its representative part of the diagram.

It is not the purpose of this work to instruct in the application and use of the indicator. We must assume that the indicator is in competent hands, or its evidence will be worthless. Indicator-cards have, however, a way of telling for themselves frequently if they have not been taken with a reasonable regard for the essential conditions. As the peculiarly important part of the air-card is the compression-line, it is necessary that the drum movement be correct, and that, in proportion to its length, the travel of the card shall be accurately coincident with the piston travel at all points. Cards, to be relied upon, should not be taken until the compressor has been run long enough to have attained its complete working conditions. We know that the compression of air heats it, and that the heat then in the air is communicated more or less to everything in contact with it. When the cylinder becomes heated, it has its effect back again upon the air, and until the compressor has been run continuously and at full pressure for an hour or so, the full temperature of the working parts has hardly been reached, and the effect of the heated parts upon the temperature of the air at different points of the stroke will not be correctly indicated. Cards aken from a compressor that has only just been started will give a lower compression-line and a lower mean effective pressure (M.E.P.) than those taken after the cylinder and piston and connecting parts have been heated up to their mean working temperature.

Fig. 3 is offered as an ideal and typical single-compression air-cylinder card, designed to show the points and properties of the card, and the methods of manipulating and studying it. The card is somewhat smoother and cleaner and in most respects more perfect than any actual

card, except that the admission-line is purposely drawn rather low to keep it perfectly distinct from the atmosphere-

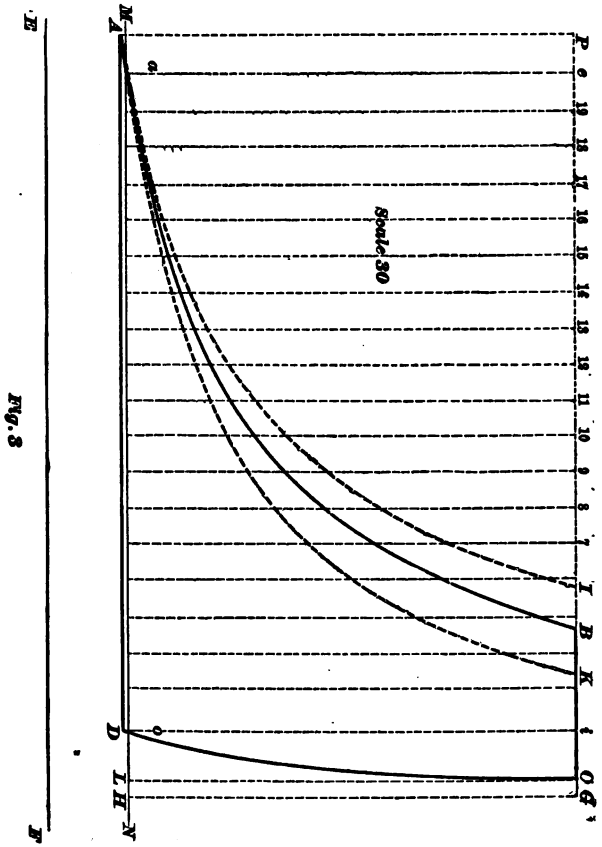


Fig. 3

line. The lines constituting the actual diagram are as follows:

AB, Compression-line
BC, Delivery "
CD, Re-expansion "
DA, Admission "

These constitute the actual card, and together represent the complete cycle of operations occurring in one end of the air-cylinder for one complete revolution of the compressor-crank. The atmosphere-line, *MN*, is also traced by the indicator, and is the neutral line of the diagram, or the line of departure in air-compression.

For the proper interpretation of the diagram additional lines are to be drawn as follows: *EF*, the line of perfect vacuum. This line is drawn parallel to the atmosphere-line, *MN*, and at a distance below it determined by the scale of the diagram. The pressure of the atmosphere at sea-level being 14.7, and always decreasing as the altitude increases, the practice of calling the atmospheric pressure 15 lbs. may be said to be a rather loose one. If the compressor is operated at a considerable altitude above the sea-level, as many are, the atmospheric pressure at the time and place where the diagram is taken should be ascertained by a barometer, and the line *EF* be drawn accordingly. It should be remembered, as we will see when we get to it, that a height of only a quarter of a mile, or a little over 1300 feet, will make a difference of 7 per cent in the volume of air furnished.

The vertical lines *PA* and *CL* having been drawn perpendicular to *MN*, and defining the extreme length of the actual diagram, the clearance-line *GH* may next be drawn. This is drawn parallel to *CL*, and the distance *CG* or *LH* may be ascertained by computation. The volume represented by the rectangle *APCL* is the actual displacement of the piston for its whole travel. The volume of air acted upon by the piston is this volume increased by the volume *CGHL* remaining in the clearance-space of the cylinder. This volume of air, *CGHL*, at the end of the compression-stroke, and at the pressure indicated by the diagram, has upon

the return stroke of the piston re-expanded until it reached the atmospheric pressure again at D. This re-expansion is so quickly accomplished that whatever the temperature at the beginning the re-expansion is practically adiabatic. The relative volume before and after the re-expansion may be found in column 5 of Table IV. Assuming the scale of the diagram to be 30 and the pressure at CG to be 70 lbs. gauge, and designating LH by x we have the proportion

$$x : DL + x :: .288 : 1$$

Then the length DL being $.25''$, we have

$$x : .25 + x :: .288 : 1;$$

then

$$x = .072 + .288x,$$

and

$$.712x = .072,$$

$$x = .101.$$

So that CG or LH equals say $\frac{1}{10}''$, and GH may be drawn accordingly.

Having drawn GH, the rectangle $APGH$ represents the total volume of air subjected to compression for the stroke, and noting the point a, at which the compression-line begins to rise from the atmosphere-line, and drawing the perpendicular ae, then $aeGH$ represents the total volume of air at atmospheric pressure. The point a, being the point at which compression from atmospheric pressure begins, may be considered the beginning of the whole diagram, and the cycle of operations for the entire stroke may be considered to start from this point.

For computing the mean effective resistance the entire enclosed area of the actual diagram $ABCD$ is to be taken,

and this area may be measured by the planimeter, or by the mean of a series of ordinates in the customary way, as with any other diagram. The area lying below the atmosphere-line of course represents the resistance upon the return stroke, but the diagrams from both ends of the cylinder being assumed to be similar, the entire area may be taken for the single stroke. The correct practice is to take diagrams from both ends of the cylinder, and it should be followed if possible, but it is clearer and simpler for us here to consider only the single diagram.

The M.E.P. of the diagram having been ascertained, the indicated horse-power (I.H.-P.) represented may be computed precisely as in the case of a steam-engine. Thus the M.E.P. in the diagram before us happening to be 30, if it were taken from a cylinder 20″ dia. × 24″ stroke at 80 revolutions per minute, the I.H.-P. for the double stroke will be as follows:

$$20^2 \times .7854 \times 30 \times 4 \times 80 \div 33{,}000.$$

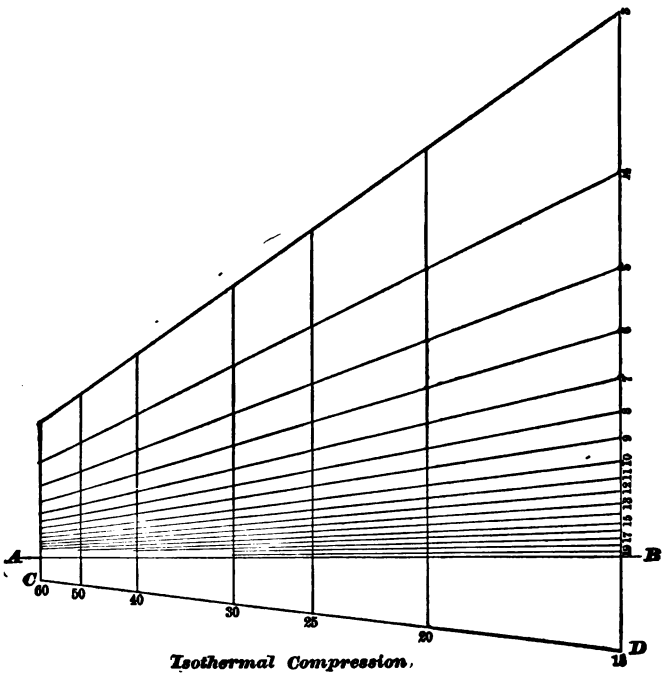
I like always in such cases to put it down in this way, that I may be sure that I get in all the ingredients. It is not necessary to run for a table of squares or of areas, and no time is saved by doing so. The decimal .7854 is always cleanly divisible by the constant divisor 33,000, giving us .0000238. It is not difficult to remember this or to keep it posted with other labor-saving devices in a convenient place. The ciphers in the other factors will help us to elbow the decimal point to the right, and our case will then stand like this, a little string of simple and easy multiplications:

$$2^2 \times .238 \times 3 \times 4 \times 8 =$$
$$.238 \times 384 = 91.39 \text{ I.H.-P.}$$

We will not here go into the question of the additions to be made to this for friction, etc.

The I.H.-P. having been ascertained, that gives us the power consumed, or the cost of the compression, and then we naturally want to know as soon as possible the actual quantity of air compressed and delivered, or how much we have got for our money. The indicator-diagram shows this very accurately. At the point *a*, where the compression-line takes its departure from the atmosphere-line, the cylinder is shown to be full of air at the atmospheric pressure and corresponding density. This is not the whole cylinder, as a portion of it, *Aa*, has been already traversed by the piston. Whatever proportional distance the point *a* may be from the beginning of the stroke is to be deducted from the total length of the stroke and the remainder represents the total actual volume of air at atmospheric pressure subjected to compression for that stroke. The compression and delivery of the air goes on with the advance of the piston until it reaches the extreme end of its stroke at *CL*, but when that is reached, the clearance-space *LCGH* is filled with air compressed, but not delivered, and upon the return of the piston this air re-expands until it reaches the atmosphere-line at *o*, so that practically the travel of the piston from *o* to *L* and back again has accomplished nothing toward compression, and the distance *oL* is also to be deducted from the total length of the line *AL*, when that line is taken to represent the volume of air compressed and delivered. In the diagram before us if *AL* be $3\frac{7}{8}''$ and *ao* be $3\frac{7}{16}''$, the ratio of air compressed and delivered is $\frac{3{\cdot}4375}{3{\cdot}875} = 88$ per cent of the cylinder capacity. As was remarked, this diagram does not represent actual practice, and the ratio is not usually as low as this, being more frequently found hovering about 5 per cent in the best compressors, and rarely below that.

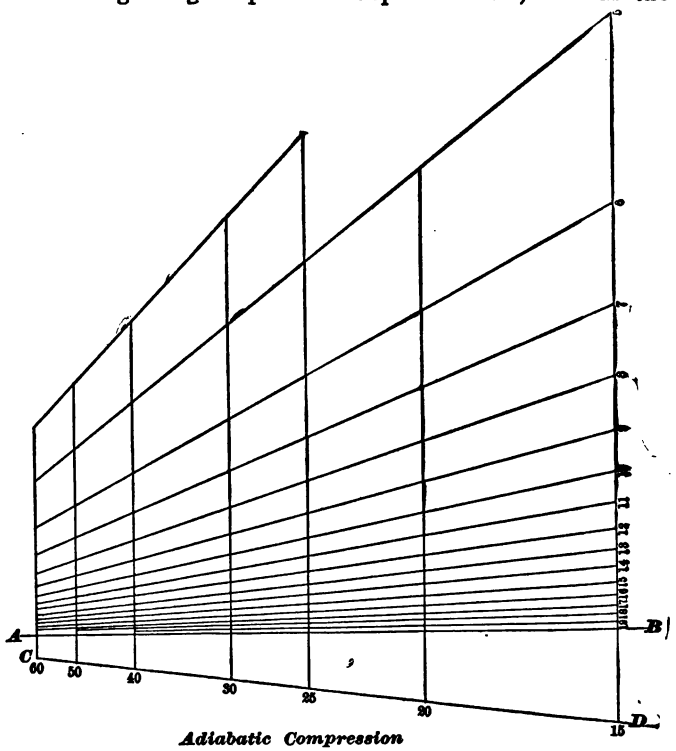
So far as the indicator has anything to say about the economy of the air-compression,—and it has much to say, —its evidence is found chiefly in the compression-line of the diagram, and for comparison it is necessary to describe upon the diagram the theoretical isothermal and adiabatic



Isothermal Compression,
Fig. 4

curves. To facilitate the drawing of these lines the diagrams Figs. 4 and 5 have been provided. The dimensions of the book have made it necessary to engrave these at one half of the full size. They can readily be reproduced in full size by any draughtsman, and will be found useful for the purpose for which they were designed. As they stand here they are correct for scales that are double those indi-

cated. Thus the 15 ordinate is correct to apply to a 30-scale diagram, the 20 ordinate for a 40-scale diagram, etc. The compression-line of the air-card is more easily studied than the expansion-line of the steam-card, as it always has a definite beginning or point of departure at *a*, such as the



Adiabatic Compression
Fig. 5

steam-card never has. From this point *a* the isothermal and the adiabatic curves are to be drawn. When the compressing piston is at *ae*, the air under compression includes the contents of the clearance-space at the farther end of the cylinder, and the total body of air under compression is represented by the rectangle *aeGH*. Vertical lines then

are to be drawn dividing this space into 20 equal sections, and for convenience the lines are to be numbered, beginning at the line next to *ae*, 19, 18, 17, 16, etc. It will not be necessary to number the last two or three lines to the right, or even to draw them, as the curves will not reach them. It will be noticed that the numbering does not include the boundary-lines *ae* and *GH*. Referring now to the diagram Fig. 5, for drawing the adiabatic curve, *AB* is the atmosphere-line and *CD* is the line of perfect vacuum, or the zero line of absolute pressure. Taking from the diagram, Fig. 5, the ordinate line corresponding to the scale of the indicator-card, the distance between *AB* and *CD*, measured upon this line, is the distance between the atmosphere-line and the line of perfect vacuum, and the vacuum-line may be drawn upon the card accordingly parallel to the atmosphere-line and at this distance from it. Then upon the same vertical line of the diagram Fig. 5 the distance from *AB* to the first intersecting line above it indicates the distance to be laid off upon the vertical line No. 19 of the card as one point of the required adiabatic curve. The distance from *AB* to the second line above is the distance to be laid off upon the vertical line No. 18 as another point of the required curve, and so on: the points may be successively laid off upon the vertical lines of the card until the delivery-line *BC* is reached, or a little above it, when it is unnecessary to go further, and the required curve may be drawn coincident with the points that have been thus located. The isothermal curve may be drawn in the same way by the aid of Fig. 4. The points upon the first two or three vertical lines to the left may be so close to the actual compression-line of the card, or so nearly coincident with it, that it is more confusing than helpful to draw the lines, and they may begin at a point further along the line

This diagram, Fig. 5, assumes the atmospheric pressure to be 14.7 lbs., and is only applicable for approximately that pressure. If the atmospheric pressure for the altitude at which the compressor works, and where the indicator-card was taken, is decidedly less than 14.7, the atmosphere-line drawn by the indicator will represent that pressure and will not represent 14.7 lbs. The mean effective pressure can of course be computed by taking the area of the indicator-card as it stands; but if it is desired to draw the adiabatic and isothermal curves by the aid of our diagrams, Figs. 4 and 5, it will be necessary to first draw a horizontal line representing the atmospheric pressure of 14.7 lbs. To do this first draw the zero line at a distance below the existing atmosphere-line corresponding with the ascertained atmospheric pressure and the scale of the diagram. Column 1 or 2 in connection with column 4 of Table IV., given at the end of this chapter, will generally furnish the data necessary for this service. The zero line having been drawn the sea-level atmosphere-line may then be drawn 14.7 lbs. above according to the indicator-scale. When this line is drawn the point where the compression-curve crosses it may be noted and also the point where the reexpansion line strikes it, and ignoring the original atmosphere-line drawn by the indicator, the adiabatic and the isothermal curves may be drawn precisely as previously discribed.

These adiabatic and isothermal curves when described are rather an aid to the eye in making comparisons with the actual compression-line of the indicator-card than necessary in computation. The mean effective of the card is ascertained by the planimeter or by measurement, and the mean effective for adiabatic and isothermal compression under the same conditions may be found in Table II, and the economy of the actual compression may be learned by com-

parison with them. This paragraph is only meant to apply to approximately sea-level computations.

Table IV will be found convenient in computations upon air-compression at various heights above the sea-level. Column 7 gives the values of the volumes of air actually compressed at any given height as compared with equal volumes of free air at sea-level.

TABLE IV.

TABLE OF ABSOLUTE PRESSURES, BOILING-POINTS, ETC., AT DIFFERENT HEIGHTS ABOVE SEA-LEVEL.

1	2	3	4	5	6	7
Height above Sea-level, Feet.	Barometer, Inches of Mercury.	Boiling-point, Degrees Fahr.	Absolute Pressure, Lbs.	Weight of 1 Cu. Ft. of Air at 60°, Lbs.	Volume of Air Equal to 1 Cu. Ft. of Free Air at Sea-level.	Volume of Free Air at Sea-level equal to 1 Cu. Ft. at given Altitude.
0	30	212	14.7	.0765	1	1
512	29.42	211	14.41	.07499	1.02	.98039
1025	28.85	210	14.136	.07356	1.04	.96154
1539	28.29	209	13.86	.07213	1.06	.9434
2063	27.73	208	13.587	.07071	1.08	.9259
2589	27.18	207	13.318	.0693	1.10	.90909
3115	26.64	206	13.054	.06793	1.12	.89285
3642	26.11	205	12.794	.06658	1.14	.87719
4169	25.59	204	12.539	.06525	1.17	.8547
4697	25.08	203	12.289	.06395	1.19	.8403
5225	24.58	202	12.044	.06267	1.22	.8197
5764	24.08	201	11.799	.0614	1.24	.8064
6304	23.59	200	11.559	.06015	1.27	.7874
6843	23.11	199	11.324	.05893	1.29	.7752
7381	22.64	198	11.094	.05773	1.32	.75757
7932	22.17	197	10.863	.0565	1.35	.74074
8481	21.71	196	10.638	.05536	1.38	.7246
9031	21.26	195	10.417	.05421	1.41	.7092
9579	20.82	194	10.202	.05309	1.44	.6944
10127	20.39	193	9.99	.05199	1.47	.6802
10685	19.96	192	9.78	.0509	1.50	.6666
11243	19.54	191	9.57	.0498	1.53	.6536
11799	19.13	190	9.37	.0488	1.56	.64102
12367	18.72	189	9.17	.0477	1.60	.625
12934	18.32	188	8.98	.0467	1.63	.6135
13498	17.93	187	8.78	.0457	1.67	.6
14075	17.54	186	8.59	.0447	1.71	.5848
14649	17.16	185	8.41	.0437	1.74	.5747

CHAPTER VI.

THE BEGINNING OF ECONOMICAL AIR-COMPRESSION.

WHILE it may easily appear that the purpose for which compressed air is used in any given case, or the conditions under which it is applied, make the question of power economy a distinctly subordinate one, and often relatively a very little and unimportant one, still it remains that for whatever purpose we use the air the cheaper we get it the better it is for us, and considerations of economy in the compression of it are always in order, and whatever saving is effected there is necessarily a clear gain.

If we are to go into the compressed-air business "for all there is in it," the way to do it successfully and profitably is first of all to control the whole business. By this is not meant the establishment of a monopoly whereby we might have the compressing of all the air that is used, although there might be great profit in that. But with what air we do handle we cannot expect to accomplish much in the way of economy, unless we have as full control as possible of the air through each of the operations involved in its use: the compression of the air, its transmission to the place or to the apparatus where it is to be used, and its actual employment for the purpose intended. There are losses possible at several points, or at all points, along the series of operations, and there are commensurate savings to

be effected by the avoidance of those losses. The losses may be defeated and the savings accomplished rather by a concentrated than by a divided control and accountability.

Economy in air-compression should begin at the beginning, and at the beginning we first have to do with the "free air," or air at atmospheric pressure. This is our raw material, and it is of course desirable to get it as cheaply as possible. Now it so happens that in keeping our accounts of profit and loss in this business the raw material is measured out to us and charged against us not by weight, but by bulk, so that whatever air we want to use it is desirable to get it to the compressor in as small a volume as possible. The smaller the relative volume of air at the beginning of the series of operations the greater will be the profit at the end for any given service realized. The volume of free air increases or diminishes as its temperature rises or falls, which means that we should get our free air as cold as possible. The colder the air is the less it will measure in cubic feet, and we may consequently say that the colder it is the cheaper we are getting it.

It seems necessary in all of the operations with compressed air to keep the accounts of profit and loss, and the record of work done, by the volume of *free air* that is handled. This involves fewer uncertainties than if we were to base our computations upon the volume of air after compression to any given pressure, or at any later stage in its transmission or use. The air-compressor, when the necessary corrections for clearance, etc., have been determined, is a very reliable air-meter, and from it may be obtained a very close record of the free air taken in by it and compressed and delivered. After the beginning of operations the temperature of the air is such an uncertain and

variable factor, and is still of such importance in the result, that all calculations are upset by it. The absolute measure of the air operated upon would of course be its weight, but this it is not possible to ascertain in extensive practical operations.

The volume of air at common temperatures varies directly as the absolute temperature. With our air-supply at 60° its absolute temperature is 521,° and the volume of it will increase or decrease $\frac{1}{521}$ for each degree of rise or fall of temperature. In securing our supply of free air for the compressor, then, if we can get a difference in our favor of 5° by laying a pipe and leading the air in from the outside of the compressor-room, or from the shady side of the building, or from the coolest place near by, instead of using the air in the compressor-room, we accomplish a saving of about 1 per cent. If we secure a difference of temperature of 10°, which in practice is frequently quite possible, we save 2 per cent absolutely without cost, except the first cost of the pipe or box to lead the air in. I know that the average machinist or engineer, or the man who calls himself distinctively the practical man, cannot commonly appreciate these small figures, or have any respect for such small savings, but when it comes to business I do not know why they should not have the same weight as the same values have in any other of the details of business. Brokers have to live and flourish upon commissions of $\frac{1}{8}$ or $\frac{1}{16}$ of 1 per cent, but "practical" men are so wealthy that 1 or 2 per cent is not worth considering.

The pipe to convey the cool, free air from the point where we determine to take it to the compressor may as well be of wood or of cement or earthenware as of iron, and in fact such material for its non-conductivity is to be

preferred. The pipe should of course be large enough to convey the required flow of air with perfect freedom. Some of the best air-compressors of the day may be connected quite readily with an outside air-supply, and they make provision for it; others cannot easily be so connected, which is unfortunate for them.

Another point that has not hitherto received the attention that it deserves, although much more important than the preceding, is the necessity, in the interest of the best power economy, of not only getting the air as cold as possible *at* the compressor, but of getting it as cold as possible *into* the compressor. We have too readily assumed that the one covers the other, when, as a matter of fact, it never does. The temperature of the air at the cylinder and about to enter it does not guarantee the temperature of the air in the cylinder at the moment when the cylinder is filled and compression begins. It is not too much to say that the temperature of the air outside the cylinder and of that inside is never the same. Yet it is not to be forgotten that the sole object of the effort to get cool air for the compressor is to have it as cool as possible, and of as small a volume as possible, at the moment when compression begins. How cool the air may have been at any previous moment, however near, has nothing to do with the case.

In another chapter I have remarked that the air-compressor is the ideal and the only perfect field for the use of the indicator, that it is the only place where the indicator diagrams will tell the whole story both of the power expended and of the work accomplished. This is undoubtedly true, but it is a statement that is quite likely to be understood to say more than it does say. The indicator diagram from the air-cylinder does not tell all that it seems to tell, or it

tells it wrong. You may note upon the diagram the point, very near the beginning of the compression-stroke, where the cylinder, if we may believe the diagram, is filled with free air, or air at atmospheric pressure, and from that, after deducting what fills the clearance-space at the end of the stroke, we may compute the volume of free air actually compressed and delivered ; and then, later, we may realize that we have not got the volume of free air that the diagram testifies to. This is due to the fact that the diagram has nothing to say about the actual temperature of the air, either at its admission, at its discharge, or at any point of the stroke. With steam, unless it is superheated, the pressure indicated guarantees the temperature; with air the pressure and the temperature have no necessary connection. I may show you a diagram from an air-compressing cylinder where the air-admission line is almost exactly coincident with the atmosphere line, and where the compression line begins to rise above the atmosphere line immediately at the beginning of the compression-stroke, showing that the cylinder is completely filled with air at atmospheric pressure, and we may congratulate ourselves that the diagram is an excellent one in this respect ; but suppose that when the cylinder is just filled, and compression is just beginning, our cylinder is filled with air at 120° instead of at 60°, which is the temperature of the supply. It means that our cylinder holds rather less than .9 of the air that we are assuming that it holds, and which the diagram says that it holds. It means not merely that the practical capacity of the compressor is one-tenth less than we assume it to be, but that for the compression of this nine-tenths we are still expending the full power as represented by the steam-card. If the difference in indicated horse-power

between the air-cylinder and the steam-cylinder is ten per cent of the air-cylinder, or if the power ratio of the steam to the air be 1.1 : 1, it is not a bad showing. This is about the ratio obtained in the best air compressors of the day. But if this 1.1, the power of the steam-cylinder, is to be compared not with 1, the full capacity of the air-cylinder, but with .9, its actual contents, the case is quite different: .9 : 1.1 : : 1 : 1.22, which is a result not worth bragging about by any compressor builder.

There seems to be no means of ascertaining the actual temperature of the air during the operation of compression. The temperature of the air at different points of the stroke would be easily computable from the indicator diagram, which shows the pressure attained at any point, if we only knew the initial temperature, but as we have no means of knowing the initial temperature we do not know the actual temperature at any time. Who will tell us how to find it out? This does not seem to be an impossible problem. It looks at first sight almost as simple—not quite—as to tell how fast a stream of water flows through a pipe. But nobody has yet invented a satisfactory water-meter. In the meantime we can only use our mechanical judgment and common sense as to the best means of getting the air into the cylinder as cool as possible. We can say in a general way that the air should enter the cylinder by the shortest and most direct possible passage, and with as little contact as possible with any metal at a higher temperature than its own.

Some interesting matter bearing upon the topic we are speaking of is found in a paper upon "Blowing Engines," by Mr. Julian Kennedy of Pittsburgh, read before the Mining Engineering Division of the World's Engineering Congress at Chicago. Mr. Kennedy says:

"This heating of the incoming air expands it, and proportionately reduces the weight of air entering the cylinder at each stroke. I have observed this in the case of an engine which was so constructed as to cause the air to travel about 3 inches over the hot metal in thin films $\frac{3}{16}''$ thick. Alongside of it was another engine of the same size and make, except that valves were used which allowed the air to pass over about 1 inch of metal, the openings being of such size that each stream of air was 2 inches in thickness. Careful and repeated tests of these engines, when both were in good order, showed that, while the indicator diagrams were practically the same, the one with the large valves would burn about 10 per cent more coke in the furnaces, a result which could only be explained on the supposition that, in the case of the engine with the small air openings, the incoming air, in passing through the small and tortuous passages in the heads, was heated about 25° C. more than in the case of the other engine."

The above, it should be remembered, speaks only of blowing engines, where the air-pressures are low, and where the heat of compression and the heating of the parts in contact with the compressed air do not range high. In an air-compressor every part of the cylinder in contact with the air after compression naturally becomes much hotter than in the blowing-engines that Mr. Kennedy speaks of, and the heating of the inrushing air may also be much greater.

The air remaining in the clearance space of the air-cylinder at the end of the compression-stroke, being between the hot piston and the more or less heated cylinder head, may not have lost much of its heat of compression, but by the cooling action of the water-jacket it must have lost some of its heat, and its temperature cannot therefore be as high as the theoretical temperature due to the compression.

Still it is comparatively hot, and when it is remembered that this hot air becomes a part of the next cylinder full of air to be compressed it has been assumed that therefore the mean temperature of the contents of the cylinder is somewhat increased by this admixture. But this conclusion is hasty and unwarranted. This hot air in the clearance-space is only hot when under the terminal pressure, and as at this pressure it is not as hot as the theoretical temperature for the given compression it cannot upon its re-expansion to atmospheric pressure be as hot as it was before its previous compression began. It must be really somewhat cooler than the air that rushes in to fill the cylinder for the next stroke, and it therefore does not contribute any heat to the new charge of air, but rather receives some heat from it and slightly cools it.

The air remaining uncompressed in the clearance-space at the end of the compression stroke, as it does not raise the temperature of the incoming air or tend to increase its volume, has therefore no bad effect in that respect, and in no way increases the power required for compressing a given quantity of air. The power that has been expended in the compression of this air in the clearance-space is not lost, or but a portion of it, as it gives out in its re-expansion, by helping the piston upon its return stroke, most of the power expended in its compression. Clearance in the air-cylinder, therefore, represents a loss of capacity in the air-compressor rather than a loss of power. And it is on account of its reducing the capacity of the compressor to compress its full quota of free air per stroke that it is desirable to keep the clearance as small as possible.

CHAPTER VII.

OF COMPRESSION IN A SINGLE CYLINDER.

PROCEEDING now to look into the actual conditions of practical air-compression, and the possible economy to be attained, it is perhaps most proper to consider the performance of the best compressors in actual use rather than the ideal, and perhaps in some respects the practically impossible, compressor. The air-compressors now most generally in use have horizontal, double-acting air-cylinders more or less completely water-jacketed, and with various devices for heads, valves, pistons, etc. The entire compression is effected at a single operation and the pressure of the air usually ranges from 60 to 80 lbs. gauge. Whether these compressors prevail through the operation of the law of natural selection and the survival of the fittest we may not rashly say; while they may not exhibit the highest attainable economy in the compression they are found to require little looking after, cost little for repairs, are generally reliable, and in the long run they are found to pay.

Supposing that we are filling the air-cylinder by the natural inflow of the air under the pressure of the surrounding atmosphere, and that we have got into the cylinder the greatest possible actual weight or quantity of air under those conditions, which means that our air is little, if any, below the density of the surrounding air from which

it is drawn, and, assuming that the air is also as cool as we can get it, we may then be said to have got our material as cheaply as possible, to have started our business under the most favorable conditions, and with encouraging prospects; and we may then, and not until then, consistently and without reproach look for the available means of economy in the actual operation of compression. The same considerations that tend to economy in the procuring of the air, or of getting it into the cylinder, hold good also in all the subsequent operations of compression. The smaller the bulk or volume of any given quantity or weight of air the cheaper can the compression be effected and the better will be the economy; and, as the volume of the air at any given pressure depends upon its temperature, the supreme consideration throughout the operation is to keep the air as cool as possible. The question of temperature is the important one to be kept constantly in sight, and its importance resides entirely in its effect upon the volume of air operated upon. While, as we know, practical air-compression has not as yet come down to the minute economies, where eventually the profits of legitimate business are to be sought, still the losses that are possible in compression, and the gains that are to be effected by avoiding or overcoming those losses, have received more or less attention from the compressor builders.

It is well enough understood that, in the interest of power economy, the air should be kept as cool as possible at every stage of the compression, and the earlier the cooling is effected the greater is the gain, as all of the subsequent operation is more or less affected by it. Keeping the air cool during compression means actually cooling the air during compression. No compression can be effected

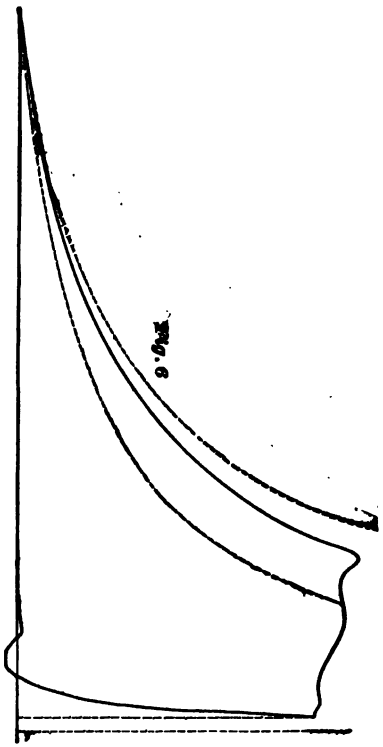
without a corresponding rise of temperature in the air compressed. Theoretically the rise will always be the same where the conditions are identical. Starting with a given volume of air and with the air at a given pressure and temperature, and compressing to another and higher pressure, the resulting volume and temperature should always be the same. Practically the temperature of the air after compression, or during compression, is never as high as the theoretical temperature, or as high as the books and tables say that it should be, and it is also widely variable under apparently slight changes of conditions. This is not at all because the theory in the case is incorrect, but rather that it is incomplete, in that it is not cognizant of all the conditions that affect the case. Theory says, and correctly, that the element of time has nothing to do with the heat of compression; that a given volume of air when compressed to another given volume will have its temperature raised so much, whether it takes a minute, an hour, or a week to do it. Practically time has a great deal to do with the case. The readiness with which the air will receive heat from or impart it to whatever may be in contact with it, and the small amount of heat actually represented by its changes of temperature render the actual volume a highly elusive quantity, and time becomes a playground for it.

In a compressing-cylinder in actual use all the parts of it, the body of the cylinder, the heads, the piston and rod, the valves and seats or guides become heated by their contact with the compressed air; but while they are thus becoming heated they are only heated by this contact, and while being heated they are also being cooled, as they are constantly transmitting some of the heat received from the air and dispersing it by conduction or radiation; and, con-

sequently, these parts are never as hot as the air that heats them—when the air is at its hottest—and the air also is not as hot as it would have been but for its contact with them. The metallic parts after a time of continuous operation attain an average temperature, and will not get any hotter. The mean temperature attained will depend upon the facilities provided for taking the heat away. Nothing better is known or has been suggested for conveying away the heat than cold water. It is now the general practice to make the shell of the cylinder double with a water-space between the cylinder proper and the outer shell, and, where the style and arrangement of the valves permit, the heads also are made hollow, with water circulating in them. Water has also in some cases been circulated in the body of the piston. These arrangements undoubtedly help to reduce the mean temperature of the parts and to make them more effective in cooling the air.

When the entire compression is effected in a single cylinder the heat of compression is abstracted from the air mostly at the latter part of each stroke, when the air is at its hottest and when the difference in temperature between the air and its surroundings is the greatest. Indeed it is to be supposed that in active compression the air loses none of its heat of compression during the earlier part of the stroke unless the means of cooling the cylinder parts are unusually efficient and operative. If at the beginning of the stroke the cylinder is hotter than the air, as it naturally must be, the air is naturally heated rather than cooled by the contact. Practical evidence of this is not wanting. Indicator diagrams from air-compressing cylinders are easily to be found, as Fig. 6, where the compression-line of the diagram does not leave the adiabatic line until the first

quarter of the stroke is traversed. In this connection it may be remarked that for evidence upon the point that we are considering any indicator-cards that are taken when a compressor has just been started, and before the cylinder



parts have attained their full average temperature, are not not be considered. Such cards promise better than the actual performance of the compressor will fulfil.

The heating of the air does not continue throughout the whole stroke of the piston, but is accomplished and ceases at the moment that the full pressure is reached; and for the

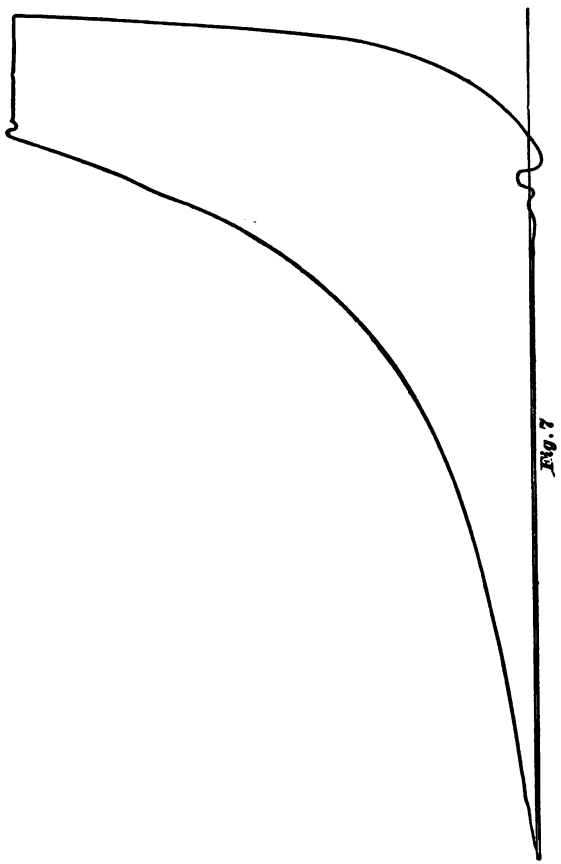
remainder of the stroke, while the compressed air is being ejected from the cylinder, the air is becoming somewhat cooler, while the metal inclosing it is becoming hotter. The heat of the cylinder parts is not evenly distributed. The ends of the cylinder and the entire cylinder-heads, being exposed to the air when it is hottest, naturally become hotter than the middle of the cylinder, which never feels the hottest air. The importance of the water-jacket, in the absence of any better cooling device, is obvious enough. The cooling effect of the water is greater when it is applied to the cylinder-heads than anywhere else, because they are exposed to the heated air for the greater portion of the stroke, while the inner surface of the cylinder itself is covered by the advancing piston. Apart from the cooling of the air under compression, and the reduction of its volume, the water-jacket is a necessity as affecting the lubrication of the cylinder surfaces. Without some such means of cooling the cylinder it would become so heated as to burn the oil and render it useless as a lubricant.

As the ultimate object of the water-jacket is the saving of power, by the reduction of the volume of air under compression, it is an interesting question as to what is practically accomplished by it. What cooling of the air is actually effected and what saving of power is accomplished by complete water-jacketing? From all that I have been able to observe I think that we may say that when compressing in a single cylinder to from 60 to 80 pounds gauge-pressure, and at a piston-speed not exceeding 300 feet per minute, one half of the total possible cooling is all that may be expected to be accomplished. This, I think, may be done, although I will not undertake at this writing to show where such a performance is actually to be found,

If by a single compression we can produce a compression-line midway between the adiabatic and the isothermal lines we are leaving but a narrow margin for further saving; and if that saving is to be accomplished by complications of mechanism, by increased friction and clearance losses, and by additional cost of maintenance, it will be but a doubtful gain.

The device of cooling the air by the injection of a spray of water into the cylinder is probably the most effective cooling arrangement that has ever been devised, but collateral objections have driven it completely out of use, in all new compressors at least, in the United States. When the spray is used the success of it as an air-cooling agent is entirely dependent upon the mode of its application. The spray can only possibly effect the intended purpose when diffused through the air while it is being compressed, or during the compression-stroke of the piston. It can only cool the air while it is hot, or while it is being heated; so that to admit the water with the incoming air is only to let it fall inert and useless to the bottom of the cylinder, to be driven out by the piston. Air so admitted may have a *quasi* usefulness in filling the clearance-space at the end of the stroke, but it can do little or nothing toward cooling the air. The presence of the water may also make it unsafe to run the compressor at a speed that would be otherwise safe and proper. With the use of water in the compression-cylinder, whether properly injected or not, no satisfactory means of lubricating the surface of the cylinder has ever been found, so that the friction of the piston and the loss of power by that means is greater than with other systems of compression. The piston and cylinder surfaces also wear away rapidly, so that the repair cost and incon-

venience is greater than with other systems. While there is no compressor-builder, that I know of, who is now offering a compressor furnished with injection-pumps, there



is no objection to any builders retaining in their catalogues, as they do at this writing, the standard arguments against the injection system, because it helps to give the catalogue

a formidable appearance, you know, and no one is harmed by the practice.

The size of the compression-cylinder is a thing to be thought of in the consideration of economical air-compression. Other things being equal, a cylinder of small diameter has a decided advantage over a large one in cooling the air during compression. In a large cylinder the portion of air immediately in contact with or lying near to its water-cooled surfaces will be cooled by the contact, but the air in the middle of the cylinder will be little and slowly affected. A number of small compressors will show better results, as regards the cooling of the air, than a large compressor can show. This has something to do with an indicator-diagram that I now have the pleasure of offering (Fig. 7). I have no hesitation in saying that it is the best and most satisfactory diagram made by a single compression that I have ever seen. The scale of the diagram is 30. It was taken from one of a series of small compression-cylinders entirely submerged in water. The speed, 96 revolutions, was not slow, so that the result was remarkable. This diagram at least shows conclusively the possibility of compressing in a single cylinder with the compression-line well within the mean of theoretical adiabatic and isothermal compression.

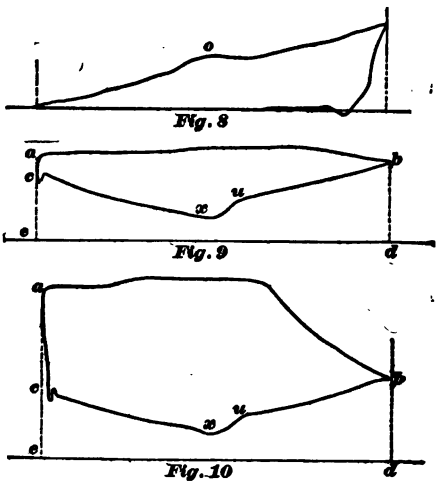
CHAPTER VIII.

TWO-STAGE AIR-COMPRESSION.

WHAT may be called the common working-pressure for compressed air, or the pressure at which the air is most frequently used, is from 60 to 80 lbs. gauge, or say 75 lbs., or 6 atmospheres. This is the usual pressure employed in operating rock drills, hoisting-engines, pumps, and the general line of mining, tunnelling, quarrying, and rock-excavating machinery, and this is even now the largest general field for the use of compressed air. While most of the compressed air that is used is compressed in single air-cylinders, usually double-acting, each cylinderful of free air being compressed and delivered by each single stroke of the piston, some of the air is compressed by two-stage compressors, or by compound compression, and most theorists advocate the two-stage compression system for ordinary pressures; and, as a matter of fact, the two-stage compressors maintain a respectable position among the various competitors. For high pressures two-stage or triple or even quadruple compression may be necessary, but for the pressures that are commonly employed, at least up to 6 atmospheres, the ultimate economy of two-stage compression is still an open and debatable question.

When we come to look into two-stage or compound compression, we find a number of interesting points to be con-

sidered, and the air-compressing problem becomes more complex. The conditions in detail involved in the operation of two-stage compression are perhaps better exhibited where the cylinders are single-acting, and that style of compressor we will first consider. I offer now—Figs. 8, 9, and 10—a set of indicator-diagrams, scale 80, from the air-



cylinders of a two-stage compressor. The cylinders of the compressor from which these cards were taken were each single-acting arranged tandem, the two pistons upon the same piston-rod, and doing the work of the alternate cylinders upon the alternate strokes of the engine, the steam-cylinder also being in line with the air-cylinders and actuating the same piston-rod. The cylinders were 20″ and 11¾″ in diameter respectively, and the stroke 18″. The capacity ratio of the two cylinders, deducting the area of the piston-rod in the larger cylinder, was 1 : .35. Cards were taken from both air-cylinders with the compressor de-

livering air at 35 lbs., at 40 lbs., and then by intervals of 10 lbs. all the way up to 120 lbs. The cards here presented are as good as a greater number for bringing out the peculiarities of the case. Fig. 8 is from the first or low-pressure cylinder. This card did not vary in any particular throughout the whole series from 35 lbs. to 120 lbs., and it would have continued the same no matter how high the terminal or delivery pressure of the second cylinder were carried. A tracing was made of one of these cards and laid over several others of the series, and the variation was so slight as to be scarcely discoverable at any point.

The mean effective pressure of Fig. 8 is 15.8 lbs., and the terminal pressure is 35 lbs. While the terminal pressure in this first cylinder is 35 lbs., it does not mean that if the two-stage compressor were compressing and delivering air at 35 lbs. gauge, the first cylinder would be doing all the work of the compressor. It is to be remembered that the complete work of air-compression comprises two distinct operations: the compression of the air to the required pressure, and the expulsion or delivery of the air against practically the same pressure in the air-pipes or in the air-receiver. In the case that we are now considering, where the air is delivered from the compressor at a pressure of 35 lbs., the first cylinder happens to do all of the work of compression, and none of the work of expulsion or delivery. In any case of two-stage compression, if either cylinder is to be called distinctively the "compressing" cylinder, that term always belongs to the first cylinder rather than to the second. If our two-stage compressor were delivering air at a pressure higher than 35 lbs., the first cylinder would still compress the air to 35 lbs. as before, or would do only a portion of the total compression, and of

course none of the delivery. The height to which the first cylinder will continually compress the air is determined by the relative capacities of the two cylinders modified to some extent by the cooling of the air that may be effected in its passage from one cylinder to the other. The work of the second cylinder when the compressor is delivering the air at 35 lbs. is shown by Fig. 9, taken from that cylinder. The delivery-line *ba* in this case would be a perfectly horizontal line if the movement of the piston were uniform throughout the stroke, the rise and fall of the line corresponding approximately to the acceleration and retardation of the piston.

At whatever pressure the compressed air may be delivered by the compressor the mean effective pressures for the two distinct operations of compression are never alike. The mean effective pressure for compression only is always lower than the M.E.P. for delivery only, and of course also lower than for the combined operation of compression and delivery as performed in a single cylinder. In the compression table II. columns 6 and 7 give the mean effective pressures for the whole stroke when all of the work of compression and delivery is done in a single cylinder, column 6 being for isothermal and column 7 being for adiabatic compression. In the same table columns 8 and 9 give respectively the isothermal and the adiabatic M.E.P. for the compression part only of the stroke of a single air-cylinder.

Resuming now our compound compression, and referring again to Fig. 8, we notice that its mean effective pressure—15.8—is greater than the pressures given in either columns 8 or 9 for compression only to 35 lbs., where the entire work of the compressor is done in a single air-cylinder.

The table referred to, as we have previously stated, has nothing to do with compound compression, but the comparison of figures might provoke a suspicion that in compound or two-stage compression we are doing the same work of compression as in the single air-cylinder, but at greater expense, and it is therefore proper to refer to it here. The case represented is different in more than one particular. In single-stage compression the compression is all done in the one cylinder, and throughout the entire compression-stroke the same quantity or weight of air is acted upon. In Fig. 8 we are not doing the entire compression part of the work in the one cylinder, although it is begun there, and the weight of air acted upon is not the same throughout the stroke. While at the beginning of the stroke the air acted upon is the free air contained in the first cylinder and just admitted from the atmosphere, this continues only for the first half of the stroke, and for the latter part of the stroke the whole body of air then undergoing compression consists not only of all the contents of the first cylinder that have not been expelled by the advancing piston, but also of the entire contents of the passage connecting the two cylinders, and the contents of that part of the second cylinder which has been vacated by its retreating piston. Fig. 8 shows the compression beginning at *a*, with the beginning of the stroke, and with the free air contents of the first cylinder alone. This goes on until the point *o* is reached, near the middle of the stroke, and then communication is opened with the air-passage that connects the cylinders, and through that with the second cylinder. When the previous compression-stroke of the first cylinder ended, the passage connecting the cylinders was filled with air compressed to 35 lbs., and by the action of the valves

this passage was then for a time shut off from communication with either cylinder. This passage, in fact, remains shut off from communication with either cylinder during the whole of the return stroke, while the first cylinder is being filled with a fresh charge of free air, and while the compressed air in the smaller cylinder is being expelled into the discharge-pipe and the air-receiver. When the return or intake stroke of the larger cylinder has ended, which return stroke is the delivery-stroke of the smaller cylinder, and when the compressed air has all been expelled from the smaller cylinder by its piston reaching the end of it, then the return stroke of the smaller cylinder commences, this stroke being of course coincident with the next compression-stroke of the larger cylinder. With the commencement of the return stroke of the smaller piston the air confined in the connecting passage begins to re-expand and to flow into the smaller cylinder. The pressure is thus falling in the air-passage, on account of its supplying the smaller cylinder, and at the same time compression is going on in the larger cylinder, and the pressure in it is rising. These simultaneous operations go on until at length the point *o* is reached, where the pressure in the larger cylinder exceeds the pressure in the air-passage and in the smaller cylinder, and the air from the larger cylinder begins to flow into the air-passage, and at the same time the entire contents of the air-passage and of the smaller cylinder become constituent parts of the body of air that is being compressed by the advancing piston of the larger cylinder, and thereafter until the end of the stroke the compression of the combined contents of large cylinder, air-passage, and small cylinder goes on together. The last one third of the compression-stroke in Fig. 8 and

ub in Fig. 9 or 10 represent the same operation of compression, the line in Fig. 8 showing a somewhat higher pressure than in Fig. 9 or 10 on account of the friction to be overcome in passing the valves and passages.

The mean effective pressure for the combined operation of compressing and expelling the air at 35 lbs., or for the whole operation of air-compression so termed, when performed adiabatically in a single cylinder is, theoretically, 21.6 lbs. Practically, without any special arrangements for cooling the air, the M.E.P. usually falls somewhat below the above figure, as the air inevitably loses more or less of its heat during the operation. If we consider Fig. 8 in connection with Fig. 9, they together represent the whole operation of compression to 35 lbs. by two-stage compression, Fig. 8 representing the compression of the air and Fig. 9 representing its expulsion or delivery. The mean effective pressure of Fig. 8 is, as we have seen, 15.8, and that of Fig. 9 is 16.4 lbs. But it must be remembered that the diameters of the two cylinders are quite different, and 16.4 lbs. in the 11¾″ cylinder is only equal in power to 5.65 lbs. in the 20″ cylinder, and $15.8 + 5.65 = 21.45$ lbs, a mean effective pressure quite close to what might have been expected for the entire operation of compressing air to 35 lbs. without any device for cooling the air. When we remember that the use of two cylinders instead of one for the same operation of compression means necessarily a greater first cost for the apparatus, to the builder if not to the purchaser, a larger number of parts, increasing the liability to accidents and delays, and a greater amount of friction, both in the air and in the machine, to be constantly overcome, it is evident that two-stage compression of itself costs more than single-stage compression.

While these diagrams were being taken the compressor

was run at about 80 revolutions per min., or 240 feet of piston travel per min., throughout. At this speed the indicated horse-power of Fig. 8 for the first cylinder is 18.05. and that of Fig. 9 from the second cylinder is 6.46, their sum being 24.51. Fig. 10 is from the smaller cylinder when compressing to 70 lbs. The M.E.P. of Fig. 10 being 43.4, and the indicated horse-power being 17.1, the I.H.-P. for Fig. 8 being, as before, 18.05, their sum is 35.15. When compressing and delivering air at 70 lbs., as indicated by Figs. 8 and 10, it will be noticed that the I.H.-P. of the two cylinders is nearly equal, and it would thus seem that the ratio of the cylinder capacities to each other was approximately correct for that pressure. The relative diameters and areas of the two cylinders may have been determined upon this assumption. An incomplete theory is more easily satisfied than one which takes cognizance of all the conditions.

The arrangement of the tandem, single-acting, two-stage compressing cylinders is about as bad a one as could be devised for an air-compressor, and no possible change in the relative capacities of the two cylinders can make it right. The trouble in the case is that while the sum of the indicated horse-powers as computed from the actual enclosed areas of the two cards is correct as representing the total horse-power consumed in the operation, it does not correctly represent the actual distribution of the resistances as encountered in the opposite strokes of the engine. The back pressure in the second cylinder, which thus far has not been thought of, imperatively demands recognition and accounting with as modifying the total resistances encountered. The back-pressure line, or, perhaps more correctly, the return-pressure line, *cxub*, as we have seen, starting at

c, represents for nearly one-half the stroke the re-expansion of the contents of the air-passage. This re-expansion goes on in the passage and in the smaller cylinder combined until the point *x* is reached, when the compression going on in the larger cylinder has brought its contents up to the same pressure. Then after a short interval, *xu*, occupied in securing a sufficient excess of pressure, and in reversing the movement from expansion to compression, the compression continues from *u* to the end of the stroke, when the pressure of 35 lbs. is again reached. As the whole of Fig. 8 is always the same, no matter what may be the working pressure of the compressor, so that it is not below 35 lbs., so also the return line of the diagram from the second cylinder is always the same, and the only change in the pair of Figs. 8 and 9 or 8 and 10 for different delivery-pressures is in the upper line *ba*, the compression- and delivery-line of the second cylinder. When compressing to 35 lbs. only there is no compression in the second cylinder, and its whole stroke is occupied in delivery. At the beginning of the stroke the resistance against the high-pressure piston is represented by the height of the vertical line *bd*. The resistance at any point of the stroke would be represented by a vertical line at that point drawn from the line *ba* down to the atmosphere-line, and the total resistance for the working-stroke is represented by the enclosed area, *bdea*. This means that the total back pressure, *bdec*, is to be added to, or, rather, is not to be deducted from, the work of the compression and delivery-stroke of the high-pressure cylinder. During this working-stroke of the high-pressure cylinder the low-pressure piston is making its return stroke and allowing its cylinder to refill with air at atmospheric pressure. The pressure upon each side of the low-pressure piston upon its return stroke is

practically that of the atmosphere, and therefore no resistance of any magnitude is to be taken into account as increasing or diminishing the total work of the high-pressure cylinder for its delivery-stroke. When, however, the low-pressure cylinder is doing its work of compression, it is assisted in its work by the return or back pressure of the high-pressure cylinder, which acts upon the high-pressure piston in the same linear direction as the low-pressure piston is travelling. The back pressure, *bdec*, which is added to the work of the high-pressure cylinder for its delivery-stroke, as represented by the enclosed area *bac*, is to be deducted from the work of the low-pressure cylinder for its compression-stroke as represented by Fig. 8.

If now we go over the series of indicator-cards, computing the indicated horse-power of each, adding the I.H.-P. of the back pressure to the I.H.-P. of each of the high-pressure cards, and deducting the same from the I.H.-P. of the low-pressure card, as above described, we find that the net resistance for the alternate strokes is very inequitably distributed. The figures for compressing to 120 lbs. are also given to aid the comparison, although the delivery or high-pressure card for that pressure is not shown. The case will stand like this:

M.E.P. of low-pressure cylinder 15.8 lbs., I.H.-P. 18.05.

M.E.P. of return stroke of high-pressure cylinder 20.1, I.H.-P. 7.88.

Then 18.05 − 7.88 = 10.17, the constant net I.H.-P. for the compression-stroke of the low-pressure cylinder or the return stroke of the high-pressure cylinder.

M.E.P. of high-pressure cyl. at	35 lbs.	16.4,	I.H.-P.	6.46.
" " " " " "	70 "	43.4	"	17.1
" " " " " "	120 "	65.7	"	25.89.

Then adding to these results the I.H.-P. for the return

stroke, which should not have been deducted from the delivery-stroke, we have:

6.46 + 7.88 = 14.34	when delivering at			35 lbs.
17.1 + 7.88 = 24.98	"	"	"	70 "
25.89 + 7.88 = 33.77	"	"	"	120 "

As these several results for the delivery-stroke are successively to be compared with the constant I.H.-P. 10.17 for the initial compression-stroke, it will be seen that even when delivering the air at but 35 lbs. the delivery-stroke of the high-pressure cylinder takes nearly 1½ times the power required for the return stroke. When compressing to 70 lbs. under the above arrangement the delivery-stroke takes nearly 2½ times the power of the return stroke, and when compressing to 120 lbs. it takes more than 3 times as much.

The total power required for the above compressor at the speed given is:

35 lbs.	− 10.17 + 14.34	= 24.51
70 "	− 10.17 + 24.98	= 35.15
120 "	− 10.17 + 33.77	= 43.94

The volume of free air compressed and delivered at either pressure is 262 cu. ft. per min.

The loss by friction in a two-stage compressor should be greater than in a single-stage compressor of the same free air capacity and working to the same pressure, and the total friction of single-acting cylinders must be proportionately greater than that of double-acting cylinders, so that if for a common single-stage double-acting compressor we allow 10 per cent for the total friction of the machine, it is probable that 15 per cent is not too great to allow for the arrangement that we have been considering above,

CHAPTER IX.

TWO-STAGE COMPRESSION, SINGLE-ACTING TANDEM, DOUBLE-ACTING TANDEM, AND CROSS-COMPOUND.

I REFER again in this chapter to indicator-cards Figs. 8 and 10 from the single-acting, two-stage, tandem air-cylinders delivering the air at 70 lbs. I reproduce these cards with some combinations resulting from them to show graphically how the net resistances are distributed throughout the alternate strokes.

When the compressor is in operation, both pistons are always exposed to the atmospheric pressure upon the sides nearest to each other. The other side, or the compressing side, of the larger piston is also exposed to the atmospheric pressure, or very nearly so, during its intake stroke. The compressing side of the smaller piston is never exposed to the atmospheric pressure when the compressor is in operation. During the intake stroke of the smaller cylinder, while it is receiving the air that is being compressed in the larger cylinder, its piston is subject to the pressure that is due to that initial compression. As both of the pistons are upon one rod, whatever pressure there may be upon the smaller piston when the larger piston is doing its work is just so much help for the larger piston, and consequently *cbde* of Fig. 10 is to be deducted from the total work of Fig. 8. In Fig. 11 the area *cbde*, representing this reacting pressure, has been reduced to the scale corresponding to the relative area of the larger cylinder, and has been super-

imposed upon Fig. 8. It will be seen that until the point *i* is reached the steam-cylinder, or whatever motor is em-

Fig. 11

ployed, has "less than nothing" to do, and if the compressor were running slowly, it would be apt to give a perceptible jump ahead just after passing this centre. This has been actually observed to occur in a compressor of this type. In Fig. 12 the two diagrams have been combined

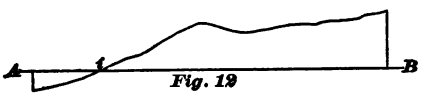


Fig. 12

into a single figure, with *AB* as the line of no resistance. This, it will be remembered, represents the distribution of the resistance for the compression-stroke of the larger piston. For nearly one quarter of the stroke, considering here the air-cylinders only, and with no reference to the driving power of the steam-cylinders, the larger piston has a force behind it greater than the resistance in front of it. From the point *i* the net resistance begins to rise before the larger piston, and continues to rise until the extreme end of the stroke, except for a slight interval at the middle. Fig. 13 represents the resistance for the return

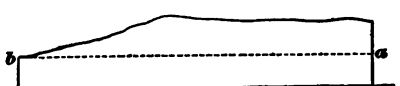


Fig. 13

stroke, which is the delivery-stroke of the smaller piston. This diagram is the same as *baed* of Fig. 10, but drawn to the scale of the larger cylinder for comparison. It has

also for convenience been reversed. It is easy enough by a glance at Figs. 12 and 13 to see the difference in the resistances for the alternate strokes. If the compressor were delivering the air at 35 lbs., instead of at 70 lbs., the upper line of Fig. 13 would approximately follow the dotted line *ba*, and the resistance would be practically uniform for the entire stroke. Fig. 12, representing the alternate stroke, would remain precisely the same whether the smaller cylinder were delivering the air at 35 lbs., at 70 lbs., or at any higher pressure, and even at the lower pressure the resistance for this stroke would not be as great as for the delivery-stroke.

It is evident that the resistance for the alternate strokes could not be equalized by changing the relative capacities of the two cylinders. To decrease the smaller cylinder would indeed tend toward an equalization of the resistances by allowing the first cylinder to do more work and compress the air to a higher pressure; but to raise the pressure in the first cylinder would be to defeat the purpose for which the two-stage compression is adopted—that of allowing a cooling of the air and a reduction of its volume before its compression is too far advanced.

As Figs. 12 and 13 represent the resistances for the alternate strokes of single-acting cylinders, these resistances may be added together and we may combine them, as is done

Fig. 14

in Fig. 14, and we then have the diagram for either stroke of tandem double-acting cylinders of the same sizes. This

of course represents double the free air capacity of the single-acting cylinders. Fig. 15 is a theoretical diagram of a double-acting single-stage compression cylinder of the same capacity, the assumed compression-line being the mean of the adiabatic and the isothermal curves. The maximum resistance for the stroke in the two-stage double-acting compressor is only three fourths of the maximum resistance for the single-stage compressor. The resistance at the beginning of the stroke is not as low in the former as

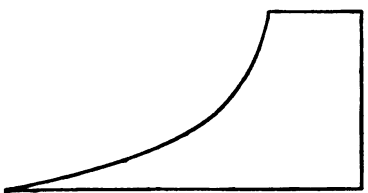


Fig. 15

in the latter, and the distribution of the resistance over the whole stroke is decidedly more uniform. As to the total effective resistance for the stroke, as we have here developed it, the two-stage, compressor shows no advantage over the single-stage even while ignoring the additional friction of the former. In fact, the mean effective resistance of Fig. 15 is somewhat less than that of Fig. 14. This might have been expected, because in the cylinders from which Fig. 14 was evolved the full benefits of water-jacketing were not employed, the cylinder-heads, for instance, not being jacketed.

We know tolerably well the importance of employing all available means (if they don't cost too much) of cooling the air while it is undergoing compression; and as the two-stage method of compression is only adopted for the sake of the cooling that may be effected between the stages, it may be

well right here to look a little into the operation of a cooler, or, as it is commonly called, an "intercooler," placed between the cylinders of a tandem two-stage air-compressor. It is assumed and asserted that by the use of the intercooler a complete cooling of the air, and of all the air, compressed by the first cylinder is effected before it is subjected to the second and final compression and delivery. Indicator-cards would show conclusively, by the relative volume delivered to the second cylinder, the actual cooling that was accomplished. I regret that I am not now able to present indicator-cards from a compressor of this type. I cannot learn that any actual cards from an American double-acting, tandem, two-stage compressor with an intercooler have ever been published.

At the beginning of the operation of compression in a compressor of this type, remembering, as I have remarked before, that the function of the first cylinder is entirely one of compression, and that, if either cylinder is to be called distinctively the "compressing" cylinder, it should be the first one rather than the second, the body of air to be acted upon by the first piston consists, at the beginning of any stroke, of the entire contents of the first cylinder and also of the air contained in the intercooler at the time and in the passages connecting the intercooler with each cylinder. As the compressing piston advances in the first cylinder the total compression-chamber at any time after the beginning of the stroke consists at that time of the remaining portion of the first cylinder still untraversed by its piston, of the intercooler and its connecting passages as before, and of that portion of the second cylinder that has been vacated by its retreating piston. The actual situation is not quite as simple as our statement of it here, as we can

see a little later. In standard compressors of the type that we are considering the piston areas and consequently the cubical capacities of the cylinders usually bear to each other about the ratio of 10 : 4. Now representing the capacity of the first cylinder by 10, that of the passage connecting it with the cooler by 2, of the cooler itself by 2, of the passage to the second cylinder by 2, and the total capacity of the second cylinder by 4, we may be able to see what the intercooler has to operate upon at any given time, and what chance it has to completely cool all the air. I assume, of course, that the cooler does thoroughly cool all the air that passes through it, and at the pressure at which it passes through. I see no reason why it should not be made efficient in this respect.

The operation at successive stages of the compression-stroke is as follows: At the beginning of the stroke of the first cylinder the entire body of air to be compressed is represented by 16, comprised like this: The contents of the first cylinder 10, passage to cooler 2, contents of cooler 2, passage to second cylinder 2. Of this volume of air only the first 10 parts, the contents of the first cylinder, is "free air." The remainder, the contents of the cooler and the connecting passages, having been compressed upon the previous stroke to the pressure at which the air is finally delivered to the second cylinder, and at the end of the stroke having been shut off by itself apart from either cylinder, stands now at a pressure somewhat above 35 lbs. gauge. As the stroke goes on, and the piston of the second cylinder recedes, this air in the cooler and passages begins to re-expand, and to flow into the second cylinder, and the pressure of this air consequently falls. At the same time compression is going on without cooling in the first cylin-

der. The total free air contents of the first cylinder are compressed independently until the middle of the stroke is reached, or a little beyond that, and a pressure of about 20 lbs. is attained in the cylinder without any of the cooling and power-saving effects of the intercooler being felt upon it. Practically none of the air of any compression-stroke flows through the intercooler until after the middle of that stroke is reached. Assuming that the pressures in the compressing cylinder and in the cooler and passages have become equal when the middle of the stroke is reached, and that at that point the piston of the first cylinder begins to act upon the whole body of air at once, the air then under compression will be: Contents of first cylinder 5, of passage to cooler 2, of cooler 2, of passage to second cylinder 2, and contents of second cylinder 2—total 13; and $\frac{4}{13}$ of this = .307 has already passed the cooler and can be no more cooled by it, and $\frac{7}{13}$ = .538 has not yet reached the cooler, and has been compressed thus far without any cooling effect whatever from it. At three quarter stroke the body of air under compression will be distributed as follows: Remaining contents of first cylinder 2.5, passage to cooler 2, cooler 2, passage to second cylinder 2, and contents of second cylinder 3—total 11.5; and of this body 5/11.5 = .434 has already passed the cooler and cannot be further affected by it, and 4.5/11.5 = .39 has not yet reached the cooler, and has not been cooled at all by it. When the end of the stroke is reached, the air is distributed like this: First cylinder 0, passage 2, cooler 2, passage 2, second cylinder 4—total 10; and of this $\frac{2}{10}$ = .2 has not yet reached the cooler and has undergone the whole compression from atmospheric pressure without cooling, and all of the con-

tents of the second cylinder have been compressed and heated more or less after passing the cooler.

The intercooler applied in this way would seem to be a rather crude and not very efficient device and when confidence in the virtues of the intercooler leads to the discarding of the most valuable feature of water-jacketing,—the jacketing of the cylinder-heads,—and when, for the same work of compression, two cylinders are employed instead of one, with the consequent increase of friction in the machine, and with the increased friction also of the air past a double set of valves and through longer and more tortuous passages, it would surely seem to require a voluminous argument to show in the system any superiority over the single-cylinder completely water-jacketed compressor for the commonly employed working pressures.

Figs. 16 and 17 are indicator-cards from two-stage air-cylinders operated by cross-connected Corliss engines with

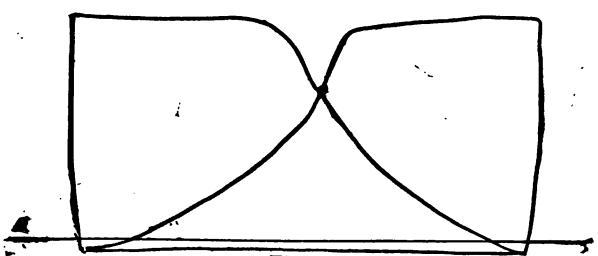


Fig. 16

the cranks at right angles. The piston rod of each steam-cylinder in this style of compressor is carried back through the head and into the air-cylinder, the low-pressure, or intake, air-cylinder being placed tandem to one steam-cylinder, and the high-pressure, or delivery, air-cylinder being connected in the same way to the other steam-cylinder.

These cards are reproduced here to show the characteristics of this style of compressor as compared with the tandem air-cylinder arrangement. They may to the general reader possess an additional interest from the fact that the original cards were taken in South Africa, where there are now installed a large number of high-duty air-compressors of American manufacture. As the cards have been twice

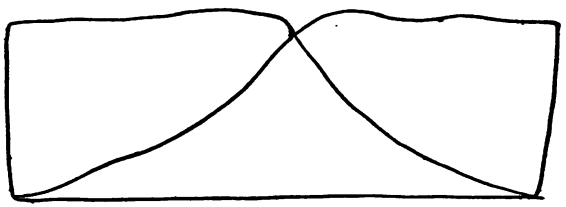


Fig. 17

retraced, they should not be too closely scrutinized. The intake cylinder was 31″ dia. × 42″stroke, and the delivery-cylinder 19.5″ dia. × 42″ stroke. The cards were taken with the compressor running at 40 revolutions per minute. The scale of the first card is 20, and that of the second card is 60.

CHAPTER X.

THE POWER COST OF COMPRESSED AIR.

WHAT is the actual power cost of a cubic foot of compressed air at any given pressure? This is only one end of the question of economy in employing compressed air for power transmission, and besides the ends of it there is a middle of some magnitude. The question of practical economy has many complications, and whether air shall be employed in a given case may be determined by considerations far removed from those that we would recognize as bearing upon the economy of it. There are many cases where at the present time the use of compressed air is imperative, whatever its cost; but still as the bill has to be paid it is well to compute it. In considering the actual cost of compression we will not now look into all the possible economies of the case, but will try to get at the actual cost according to the common practice of air-compression at the present time.

Say, then, that we have a steam-actuated air-compressor, with steam- and air-cylinders both 20″ dia. × 24″ stroke, at 75 revolutions per min., using steam at 80 lbs. and compressing air to 80 lbs. The case will then be like this:

Power required by air-cylinder:

$$20^2 \times .7854 \times 36.6 \times 300 \div 33{,}000 = 104.53 \text{ H.-P.}$$

$$104.53 + 10 \text{ per cent.} = 114.98 \text{ H.-P.}$$

Volume of free air compressed by air-cylinder:

$$20^2 \times .7854 \times 300 \div 144 = 654.5.$$
$$654.5 - 10 \text{ per cent} = 589 \text{ cu. ft. free air.}$$
$$589 \times .1552 = 91.4 \text{ cu. ft. at 80 lbs.}$$

Power of steam-cylinder (steam 80 lbs., cut-off .25, M.E.P. 40.29):

$$20^2 \times .7854 \times 40.29 \times 300 \div 33{,}000 = 115.06 \text{ H.-P.}$$

Volume of steam used:

$$20^2 \times .7854 \times 75 \div 144 = 163.62.$$
$$163.62 + 10 \text{ per cent} = 180 \text{ cu. ft.}$$

Here 180 cu. ft. of steam at 80 lbs. produce 94 cu. ft. of air at 80 lbs., or 1 cu. ft. of air at this pressure costs nearly 2 cu. ft. of steam. It should be remembered that the same ratio will not necessarily hold good for other pressures. For lower air pressures the steam will have a little more advantage, and for higher pressures it will have a little less. The mean effective resistance assumed for the air-cylinder is the theoretical resistance with no cooling of the air. In practice the actual resistance is somewhat less than this, but the difference between the air- and the steam-cards, or the friction loss of the machine, is also usually more than 10 per cent, so that few of the common compressors in use will at their best give any better results than the above.

The following table, V, gives the horse-power required to compress one cubic foot of free air per minute to a given pressure, also the horse-power required to furnish a cubic foot of air at the given pressure; or, in other words, the power cost of the operation of air-compression is exhibited

TABLE V.

TABLE SHOWING THE HORSE-POWER REQUIRED TO COMPRESS 1 CUBIC FOOT OF FREE AIR PER MINUTE TO VARIOUS GAUGE PRESSURES, ALSO THE POWER REQUIRED TO DELIVER 1 CUBIC FOOT OF AIR AT THE GIVEN PRESSURE.

1 Gauge Pressure.	Compressing 1 Cu. Ft. of Free Air per Min. to given Pressure.		Delivering 1 Cu. Ft. per Min. of Air Compressed to the Pressure given.	
	2 Compression at Constant Temperature.	3 Compression without Cooling.	4 Compression at Constant Temperature.	5 Compression without Cooling.
5	.01876	.01963	.02514	.0263
10	.03325	.03609	.05586	.06399
15	.04507	.05022	.09105	.10145
20	.05506	.06283	.12994	.14829
25	.06366	.07422	.17191	.20043
30	.0713	.08464	.21678	.25734
35	.0782	.09425	.26445	.31872
40	.084305	.10324	.31375	.38422
45	.08954	.11166	.36368	.45353
50	.09508	.11952	.41848	.52605
55	.09936	.12702	.47112	.60227
60	.10402	.13418	.52855	.68181
65	.10808	.14028	.58612	.76079
70	.11245	.14718	.64812	.8483
75	.11629	.15373	.70952	.93795
80	.11926	.15971	.76843	1.02906
85	.1224	.16555	.83039	1.1231
90	.12558	.17096	.89444	1.2176
95	.12886	.17629	.96164	1.3148
100	.13121	.18153	1.0243	1.4171

both from the beginning and from the termination of it. From either standpoint the power required is given both for isothermal and for adiabatic compression, in the one case assuming that the air remains at its initial temperature during the compression, and in the other case that the air as heated by the compression is not cooled during the operation. The power required as given in the table is the

theoretical power, and no allowance is made for the inevitable losses of power that occur in its actual application, and of course it makes no difference what may be the source of the power, or the economy with which it may be developed or applied. The power employed may be steam, with or without cut-off or condensation, water-power, electricity, manual power, or anything else. When the volume of free air required to be compressed per minute is known, or the volume of air at the given pressure required to be furnished, the theoretical power required may be found by multiplying the number of cubic feet required by the power required for 1 foot, as here given. In the last column of the table although the compression is assumed to be adiabatic the air is supposed after delivery to have cooled to normal temperature, and to have assumed its practically available volume, and the 1 cu. ft. of compressed air represented in column 5 is precisely the same as the 1 cu. ft. in column 4.

In the use of this table the second column, showing the power cost of isothermally compressing 1 cu. ft. of free air to the given pressure, represents the ideal and unattainable, but still the only rational and natural, standard of efficiency in air-compression. Whatever the actual power employed may exceed the values in this column is the irrecoverable cost of compression. In comparing the performance of a steam-actuated air-compressor with this standard we shall find at least four different sources of loss in the operation of compression, and all requiring some deduction from the ideal efficiency. Few persons in dealing with compressed air recognize and make the necessary allowances and deductions for all of these sources of loss, and in consequence the efficiencies of the air-compressors of the day are gener-

ally represented to be much higher than they actually are. In deploring the low ultimate efficiencies in compressed-air systems we may still find great losses in the compression end of them, notwithstanding all the boasted "modern improvements."

The first deduction to be made is for the friction of the machine, and is accurately represented by the difference in the mean effective pressures in the air, and in the steam-cylinders, assuming the areas and strokes of the two cylinders to be the same. This difference is often found to be surprisingly low. In some large Corliss compressors, where the air-cylinders are placed tandem to the steam-cylinders, the piston-rod from the steam-cylinder being continued into the air-cylinder to operate its piston, the total loss of power in the friction of the engine often ranges as low as 5 per cent, where the friction of the same steam-engine if transmitting all of its power through its crank-shaft would exceed 10 per cent. Compressed air evidently here has a great advantage over electricity, and the first power loss in an electric system, in driving the generator by means of a steam-engine, and including the friction of the generator, is necessarily from two to three times as great as the loss in operating the air-cylinder of a steam-actuated compressor of the best type. The friction loss in the common straight-line, direct-acting air-compressors may generally be assumed at 10 per cent, and is seldom found lower than that. Some statements of air-compressor efficiencies are made upon the friction loss alone, and in the last-mentioned instance the efficiency of the compressor would be stated as 90 per cent, with no hint of any other losses, which is absurd.

The second source of loss to be reckoned with is in the

increase of temperature and reduction of weight of air admitted to the cylinder for compression. This loss is seldom recognized, and still more rarely made the subject of actual computation. It is difficult to determine it accurately, because it is the one detail in the cycle of operations in air-compression about which the indicator-diagram has nothing to say. It is evident, however, that there must be some loss from this source in almost every case. As the air is always heated by compression, and at best only partially cooled, the cylinder is heated by it, and after continuous compression becomes quite hot. Water-jacketing only partially cools the inner surfaces of the cylinder, and some parts of it and the heads and usually all of the piston are not cooled at all by the water. The air, which when heated we find to give up its heat so quickly in transmission, is also heated with equal celerity when the conditions are reversed, and it cannot pass through heated passages into a heated chamber, which the cylinder is, without being heated and increased in volume, so that a less weight or actual quantity of air is sufficient to fill the cylinder. The loss in many cases from this source is perhaps light, but in some cases there can be little doubt that it exceeds the friction loss of the compressor. If air whose normal temperature is 60° is actually at 120° at the moment when compression begins in the cylinder, the weight of air present is less than 90 per cent of the same volume at its original temperature.

The third loss of power in air-compression is due to the heating of the air during the compression, and to the greater force required for the compression on account of this heating. This is the one source of loss that is generally recognized, and too often treated of as the only one,

The loss in this case is represented by the percentage of excess of mean effective pressure above that required for isothermal compression. In compressing to 70 lbs. the M.E.P. for isothermal compression is 26, and for adiabatic compression it is 33.73, and the mean of the two is 29.87. The excess of the adiabatic above the isothermal is 29.7 per cent, and the excess of the mean above the isothermal is still 14.85, or say 15 per cent. No compressor within my knowledge does its compression to 70 lbs. with less than 15 per cent of loss except by devices that increase the friction of the machine or add to the power required or to the cost of operation in some way.

The fourth source of power loss in air-compression lies in the fact that while the indicator-cards show, as they do, that the M.E.P. for the compression-stroke is above the mean of the isothermal and the adiabatic pressures, or when compressing to 70 lbs. more than 15 per cent above isothermal compression, the volume of free air compressed is never a cylinderful. The figures in the formulas and in the tables are based upon the assumption that a certain volume of air is compressed, and when applied to the cylinder of a compressor, the actual capacity of the cylinder, or the net area multiplied by the stroke, is the volume represented. It is of course the fact that the volume actually compressed is always somewhat less than this. There is a loss at each end of the stroke. Compression of the air at full atmospheric pressure does not begin precisely at the beginning of the stroke, and all of the air is not expelled by the piston at the end of the stroke. It is customary with compressor-people to say that clearance in the air-cylinder at the end of the stroke does not mean loss of power, but only loss of capacity, because the power which

has been expended in the compression of the air filling the clearance-space is returned to the piston by the re-expansion of the air when the piston makes its return stroke. The clearance does, however, practically represent an actual loss of power, or an expenditure of power without any result, because the evidence which the clearance gives is so generally ignored, and every stroke of the piston is assumed to compress and deliver free air to the full capacity of the cylinder, which it certainly never does.

In practice these four items of loss of power in compression occur in different combinations, such as 10, 10, 17, 10 = 60.5 per cent net efficiency or 7, 2, 15, 5 = 73.6 per cent net efficiency. It is safe to say that the ultimate efficiency never goes as high as 80 per cent, while it often goes below 60 per cent. If any air-compressor builder feels aggrieved over this statement, a fine opportunity is opened for a demonstration of a higher efficiency. Indicator-cards from air- and steam-cylinders are full and conclusive evidence as to three of the four items of loss enumerated above, and it might be profitable to make an exhibit of these, and if it proved to be creditable, we could be generous in our estimates of the one concerning which no proof seems to be easily procurable.

CHAPTER XI.

THE POWER VALUE OF COMPRESSED AIR.

THOSE of us who are not wise enough to consider well before buying it what a thing will be worth to us are very apt to be looking it over anxiously after the purchase to see what sort of a bargain we have got. As in the last chapter we learned the approximate power cost of a cubic foot of compressed air at a given pressure, we now naturally want to know what it is worth to us. We realize that in the compression it is costly, if, indeed, we do not think that it costs too much, and yet we go on using it more and more, and find profit in doing so. Our bargain is really worse than appears thus far; for if we take our compressed air and go to use it as we use steam, or if we substitute it in a place where we have been using steam, as in a steam-engine, we soon find that a cubic foot of air at any given pressure is not worth as much, in power, as a cubic foot of steam at the same pressure.

The accompanying diagram, Fig. 18, shows how this can be so. Here we have 1 volume of steam and the same of air, both at 100 lbs. gauge pressure, and each successively expanded through several additional volumes until the pressure of each falls below that of 1 atmosphere. It is readily seen that the two expansion-lines are very different, and that the mean effective pressure of the steam is decidedly higher than that of the air. Thus 1 volume of

steam at 100 lbs. gauge, represented by the length of the line *A*1, reaches atmospheric pressure after expansion to about six and a half times the original volume, while the same volume of air drops to the same pressure after expan-

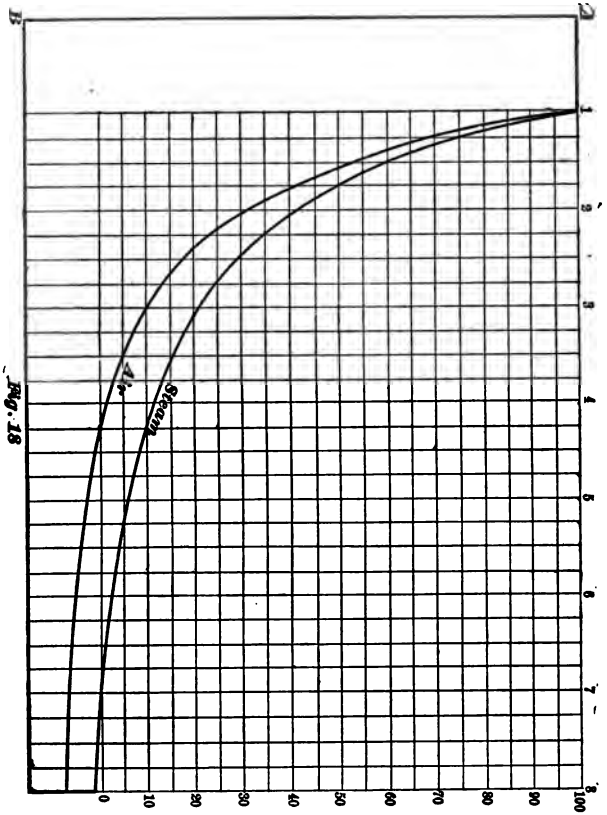


Fig. 18

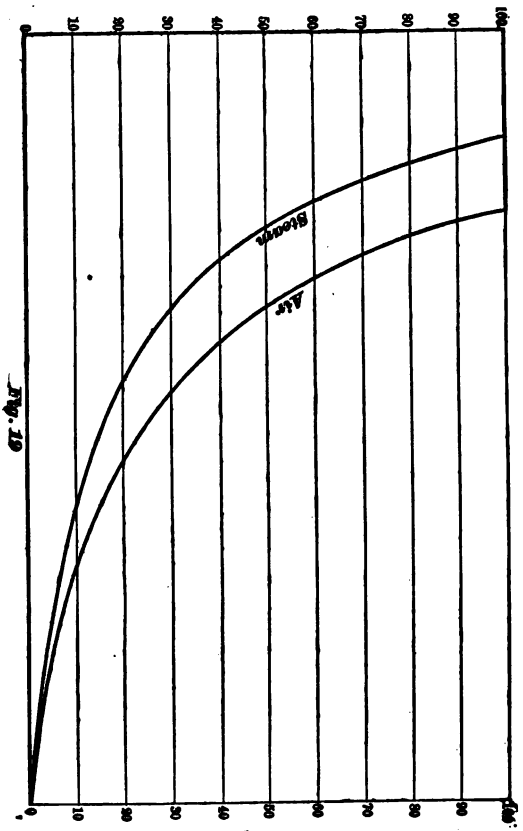
sion to a little over four times its original volume. The mean effective pressure for the steam, taking the whole extent of the diagram, or cutting off at $\frac{1}{8}$ stroke, is 27.38 lbs., while the M.E.P. for air under the same conditions is 19.51

lbs., or only 71 per cent of the former. As with this cut-off the terminal pressures are below the atmosphere, the entire mean effective pressures are not properly "effective" or available or comparable. At $\frac{1}{4}$ cut-off the M.E.P. for steam is 51.93, and for air it is 44.19, or 85 per cent, which looks a little better for the air, but in this case the terminal pressure of the steam is 11 lbs. gauge, and some of its power is lost through the exhaust.

This diagram is equally applicable for any other initial pressure below 100, by taking as the measure of volume the length of a horizontal line drawn from the line *AB* to the expansion-line at the given pressure, and taking each repetition of this length horizontally as representing an additional volume. Thus at 60 lbs. pressure 1 volume of steam is represented by $1\frac{1}{2}$, and 2 volumes would be represented by 3, and at the intersection of the vertical line marked 3 we find that the steam pressure has fallen to 21 lbs., which is nearly correct. One volume of air at 60 lbs. is represented by about $1\frac{3}{8}$ of the diagram-spacing, and 2 volumes would consequently be $2\frac{3}{4}$ of the spaces, and here we find the air pressure to be 13 +, which is the correct terminal pressure for air at 60 lbs. cut-off at $\frac{1}{2}$ stroke, or expanded to double the volume. We may take any section of this diagram as representing, theoretically, an indicator-card either for steam or air, but we cannot take both the steam- and the air-cards and compare them by placing one upon the other, because the lengths of the two cards will not coincide.

Fig. 19 is a theoretical card, scale 40, showing both steam and air expanded to atmospheric pressure at the end of the stroke. In this case the air-line is outside of and above the steam-line, and, of course, represents a higher

mean effective power, but it is at the expense of a much larger initial volume. The M.E.P. for air filling a cylinder at an initial pressure of 100 lbs. for a sufficient portion of the



stroke and then expanding (without loss or gain of heat) so that it reaches atmospheric pressure at the end of the stroke will be 41.6 lbs. The M.E.P. for steam under the same conditions will be 32.46. The volume of air used will be

.2353, while the volume of steam, wlll be .1471. If the air gave the same M.E.P. in proportion to its volume, it would be .1471 : 2353 : : 32.46 : 51.9, instead of 41.6, and the greater comparative efficiency of steam under the conditions is 41.6 : 51.9 : : 1 : 1.247, or nearly 25 per cent.

As the expansion of the air here exhibited is adiabatic, its temperature, at least for the latter portion of the expansion, would be below that of the cylinder containing it, and the air would be heated and expanded, rather than cooled, by its surroundings; so that there need be no apprehension that the expansion-line would be below the theoretical, or that there might be still some lurking losses to arise and confront us. The essential difference in an engine or motor to be driven by compressed air instead of steam is a later cut-off for the same initial pressure. This later cut-off develops the paradox that although air has less available power than steam, volume for volume, the same cylinder with the same pressure will develop more power with air than with steam, both being used at the point of highest efficiency.

I offer herewith a table, VI, showing the mean effective and terminal pressures for both steam and air at various points of cut-off and for different gauge pressures from 50 to 100. Gauge pressures are given throughout except when below atmosphere when the absolute pressures are given in **italics**. It is thought that in this way the table will be more serviceable to the general mechanic than if the absolute pressures were given throughout. Nothing is said of the initial temperature of the air, as that would not affect the rate of expansion or the mean effective pressure.

TABLE VI.

TABLE OF MEAN EFFECTIVE AND TERMINAL PRESSURES OF STEAM AND AIR AT VARIOUS POINTS OF CUT-OFF AND FOR DIFFERENT GAUGE-PRESSURES FROM 50 TO 100 LBS.

All pressures given in the table are gauge pressures, except where they fall below atmosphere, when the absolute pressures are given and printed in full face.

INITIAL PRESSURE 50 LBS.				
Point of Cut-off.	Mean Steam Pressure.	Mean Air Pressure.	Terminal Steam Pressure.	Terminal Air Pressure.
.05	12.12	8.87	2.69	.95
$\frac{1}{16}$	14.39	10.8	3.41	1.31
.10	5.44	1.2	5.63	2.54
$\frac{1}{8}$	8.95	4.51	7.13	3.47
.15	10.18	7.62	8.65	4.49
$\frac{3}{16}$	16.55	11.96	10.97	6.14
.20	17.9	13.84	11.75	6.74
.25	22.83	18.45	14.9	9.23
.30	27.11	23.05	3.08	11.93
$\frac{1}{4}$	29.66	25.84	5.22	13.83
.35	30.86	27.17	6.3	14.82
$\frac{3}{8}$	32.56	29.07	7.92	1.34
.40	34.15	30.87	9.55	2.88
.45	37.03	34.18	12.84	4.11
.50	39.54	37.12	16.12	7.49
.60	43.61	41.98	22.77	16.66
$\frac{5}{8}$	44.44	42.99	24.44	18.53
$\frac{3}{4}$	45.67	44.52	27.24	21.73
.70	46.54	45.6	29.49	24.33
.75	47.64	46.98	32.88	28.34
.80	48.52	48.08	36.27	32.47
$\frac{7}{8}$	49.43	49.26	41.4	38.85
.90	49.64	49.53	43.11	41.03

TABLE VI.—(*Continued.*)

INITIAL PRESSURE 60 LBS.

Point of Cut-off.	Mean Steam Pressure.	Mean Air Pressure.	Terminal Steam Pressure.	Terminal Air Pressure.
.05	13.99	10.23	3.1	1.1
$\frac{1}{16}$	1.61	12.46	3.93	1.51
.10	8.58	3.69	6.49	2.93
$\frac{1}{8}$	12.64	7.51	8.22	4.01
.15	16.37	11.1	9.99	5.21
$\frac{3}{16}$	21.41	16.11	12.66	7.08
.20	22.96	17.7	13.56	7.77
.25	28.75	23.6	2.19	10.65
.30	33.59	28.9	5.87	13.77
$\frac{1}{4}$	36.54	32.13	8.34	.96
.35	37.92	33.66	9.58	2.33
$\frac{3}{8}$	39.87	35.85	11.8	3.85
.40	41.71	37.93	13.22	5.64
.45	45.03	41.75	17.1	10.71
.50	74.94	45.14	20.91	13.26
.60	52.62	50.75	28.59	21.53
$\frac{5}{8}$	53.58	51.92	30.51	23.69
$\frac{3}{4}$	55.01	53.67	33.74	27.94
.70	56.01	54.93	36.34	30.39
.75	57.28	56.52	40.24	35.01
.80	58.29	57.79	44.06	39.78
$\frac{7}{8}$	59.34	59.15	50.07	47.14
.90	59.58	59.46	52.05	49.65

TABLE VI.—(*Continued.*)

INITIAL PRESSURE 70 LBS.

Point of Cut-off.	Mean Steam Pressure.	Mean Air Pressure.	Terminal Steam Pressure.	Terminal Air Pressure.
.05	1.06	11.6	3.52	1.23
$\frac{1}{16}$	3.82	14.12	4.46	1.71
.10	11.73	6.19	7.36	3.32
$\frac{1}{8}$	16.33	10.51	9.32	4.54
.15	20.55	14.58	11.32	5.88
$\frac{3}{16}$	26.26	20.25	14.37	8.03
.20	28.02	22.06	.37	8.81
.25	34.47	28.74	4.49	12.07
.30	40.07	34.75	6.65	.6
$\frac{1}{4}$	43.41	38.41	11.45	3.09
.35	44.97	40.15	12.86	4.38
$\frac{3}{8}$	47.19	42.63	14.98	6.36
.40	49.27	44.99	17.1	8.39
.45	53.04	49.31	21.38	12.61
.50	56.33	53.16	25.69	17
.60	61.64	59.51	34.4	26.4
$\frac{5}{8}$	62.73	60.84	36.58	28.85
$\frac{3}{4}$	64.34	62.83	40.24	33.03
.70	65.48	64.25	43.19	36.44
.75	66.92	66.05	47.61	41.68
.80	68.07	67.5	52.05	47.08
$\frac{7}{8}$	69.26	69.03	58.75	55.43
.90	69.53	69.38	60.99	58.27

TABLE VI.—(*Continued.*)

INITIAL PRESSURE 80 LBS.

Point of Cut-off.	Mean Steam Pressure.	Mean Air Pressure.	Terminal Steam Pressure.	Terminal Air Pressure.
.05	2.72	12.96	3.93	1.39
$\frac{1}{16}$	6.04	.78	4.98	1.92
.10	14.87	8.68	8.22	3.71
$\frac{1}{8}$	20.01	13.51	10.42	5.08
.15	24.73	18.06	12.65	6.57
$\frac{3}{16}$	31.12	24.4	1.04	8.97
.20	33.08	26.6	2.18	9.85
.25	40.29	33.89	6.78	13.49
.30	46.55	40.61	11.43	2.44
$\frac{1}{4}$	50.28	44.69	14.56	5.22
.35	52.03	46.64	16.14	6.66
$\frac{3}{8}$	54.51	49.41	18.5	7.88
.40	56.83	52.05	20.88	11.14
.45	61.04	56.9	25.66	15.86
.50	64.72	61.18	30.48	20.81
.60	70.76	68.28	40.21	31.27
$\frac{5}{8}$	71.87	69.76	42.65	34.01
$\frac{3}{4}$	73.68	71.99	46.74	38.68
.70	74.95	73.57	50.03	42.49
.75	76.56	75.59	54.97	48.35
.80	77.84	77.2	59.94	54.38
$\frac{7}{8}$	79.17	78.92	67.43	63.81
.90	79.47	79.31	69.93	66.89

TABLE VI.—(*Continued.*)

INITIAL PRESSURE 90 LBS.

Point of Cut-off.	Mean Steam Pressure.	Mean Air Pressure.	Terminal Steam Pressure.	Terminal Air Pressure.
.05	4.59	14.33	4.34	1.54
$\frac{1}{16}$	8.25	2.95	5.51	2.12
.10	18.02	11.17	9.09	4.1
$\frac{1}{8}$	23.7	16.52	11.51	5.61
.15	28.92	21.55	13.98	7.26
$\frac{3}{16}$	35.97	28.55	2.73	9.92
.20	38.15	30.78	3.99	10.88
.25	46.11	39.04	9.07	14.91
.30	53.02	46.46	14.22	4.27
$\frac{1}{4}$	57.17	50.98	17.67	7.35
.35	59.08	53.13	19.42	8.95
$\frac{3}{8}$	61.82	56.2	22.03	11.39
.40	64.4	59.11	24.65	13.88
.45	69.05	64.45	29.95	19.11
.50	73.11	69.19	33.27	24.56
.60	79.67	77.05	46.02	36.14
$\frac{5}{8}$	81.02	78.69	48.72	39.16
$\frac{3}{4}$	83.01	81.14	53.23	44.33
.70	84.42	82.9	56.88	48.54
.75	86.19	85.12	62.34	55.02
.80	87.61	86.91	67.83	61.69
$\frac{7}{8}$	89.08	88.81	76.1	72
.90	89.42	89.24	78.88	75.52

TABLE VI.—(*Continued.*)

INITIAL PRESSURE 100 LBS.

Point of Cut-off.	Mean Steam Pressure.	Mean Air Pressure.	Terminal Steam Pressure.	Terminal Air Pressure.
.05	6.45	.69	4.76	1.69
$\frac{1}{16}$	10.24	4.11	6.03	2.32
.10	21.16	13.66	9.95	4.49
$\frac{1}{8}$	27.38	19.51	12.61	6.15
.15	33.1	25.03	.31	7.95
$\frac{3}{16}$	40.83	32.71	4.42	10.89
.20	43.21	35.14	5.79	11.92
.25	51.93	44.19	11.36	1.33
.30	59.5	53.32	17	6.11
$\frac{1}{4}$	64.02	57.26	20.78	9.48
.35	66.14	59.62	22.69	11.23
$\frac{3}{8}$	69.14	62.98	25.56	13.89
.40	71.96	66.16	28.43	16.64
.45	77.05	72.02	34.23	22.36
.50	81.5	77.21	40.06	28.33
.60	88.69	85.82	51.83	41.01
$\frac{5}{8}$	90.15	87.61	54.79	44.32
$\frac{3}{4}$	92.19	90.32	59.73	49.97
.70	93.89	92.22	63.72	54.39
.75	95.83	94.66	69.7	61.69
.80	97.38	96.61	75.72	68.99
$\frac{7}{8}$	98.99	98.7	84.78	80.28
.90	99.36	99.17	87.82	84.14

TABLE VII.

TABLE OF THE VOLUME OF AIR TRANSMITTED IN CUBIC FEET PER MINUTE IN PIPES OF VARIOUS DIAMETERS.

Velocity of Flow.		Diameter of Pipe in Inches.																
Ft. per Sec.	Ft. per Min.	1	1¼	1½	2	2½	3	3½	4	5	6	8	10	12	16	20	24
1	60	.327	.623	.848	1.31	2.045	2.95	4.00	5.24	8.18	11.78	20.94	32.73	47.12	83.77	130.9	188.5
2	120	.655	1.246	1.696	2.62	4.09	5.89	8.02	10.47	16.36	23.56	41.89	65.45	94.25	167.5	261.8	377
3	180	.982	1.869	2.544	3.93	6.13	8.84	12.02	15.7	24.5	35.3	62.8	98.2	141.4	251.3	392.7	565.5
4	240	1.31	2.492	3.392	5.24	8.18	11.78	16.03	20.9	32.7	47.1	83.8	131	188	335	523	754
5	300	1.64	3.11	4.24	6.54	10.22	14.7	20.04	26.2	41	59	104	163	235	419	654	942
6	360	1.96	3.74	5.09	7.85	12.27	17.7	24.05	31.4	49.1	70.7	125	196	283	502	785	1131
7	420	2.29	4.36	5.93	9.16	14.31	20 6	28.06	36.6	57.2	82.4	146	229	330	586	916	1319
8	480	2.62	4.98	6.79	10.5	16.36	23.5	32.06	41.9	65.4	94	167	262	377	670	1047	1508
9	540	2.95	5.61	7.63	11.78	18.4	26.5	36.07	47	73	106	188	294	424	754	1178	1696
10	600	3.27	6.23	8.48	13.1	20.4	29.5	40.09	52	82	118	209	327	471	838	1309	1885
12	720	3.93	7.48	10.18	15.7	24.54	35.3	48.1	63	98	141	251	393	565	1005	1571	2262
14	840	4.58	8.72	11.87	18.3	28.6	41.3	56.1	73	114	165	293	458	659	1172	1833	2639
15	900	4.91	9.35	12.72	19.6	30.7	44.2	60.1	78	122	177	314	491	707	1256	1963	2827
16	960	5.23	9.9	13.56	20.9	32.7	47.2	64.1	84	131	189	335	524	801	1340	2094	3016
18	1080	5.89	11.21	15.26	23.5	36.8	53.1	72.1	94	247	212	377	589	848	1508	2356	3393
20	1200	6.54	12.46	16.9	26.2	40.9	59	80.2	105	164	235	419	654	942	1675	2618	3770
22	1320	7.19	13.7	18.65	28.8	45	64.9	88.2	115	180	258	461	720	1036	1842	2879	4147
24	1440	7.85	14.95	20.35	31.4	49.1	70.8	96.2	125	196	283	502	785	1131	2010	3141	4524
25	1500	8.18	15.56	21.2	32.7	51.1	73.8	100.2	131	204	294	523	818	1178	2094	3272	4712
26	1560	8.5	16.18	22.05	34	53.2	76.7	104.2	136	213	305	544	851	1225	2178	3403	4900
28	1680	9.16	17.44	23.72	36.6	57.2	82.6	112.2	146	229	330	586	916	1319	2346	3665	5278
30	1800	9.8	18.69	25.44	39.3	61.3	88.5	120.3	157	245	353	628	982	1414	2513	3927	5655
32	1920	10.46	19.94	27.14	41.9	65.4	94.4	128.3	168	262	378	670	1047	1508	2680	4188	6032
34	2040	11.11	21.18	28.83	44.5	69.5	100.3	136.3	178	278	400	712	1113	1602	2848	4450	6409
35	2100	11.44	21 80	29.68	45.8	71.5	103.2	140.3	183	286	411	733	1145	1649	2932	4581	6597
36	2160	11.77	22.43	30.53	47.1	73.6	106.2	144.3	188	294	423	754	1178	1696	3015	4712	6986
38	2280	12.42	23.67	32.22	49.8	77.7	112.1	152.3	198	311	447	795	1244	1791	3183	4974	7163
40	2400	13.08	24.92	33.92	52.4	81.8	118	160.3	209	327	471	837	1309	1885	3350	5236	7540

CHAPTER XII.

COMPRESSED-AIR TRANSMISSION.

THE accompanying table, VII, gives the actual volume of air passing through a pipe of given diameter when the linear velocity of flow is known. This is merely a convertible table of pipe capacity, and will be useful as such in determining the size of pipe best adapted for a given service, and it has nothing to do with the conditions which may determine the rate of transmission.

While in considering the operation of air-compression we base our computations upon the volume of *free air* compressed, it is better in questions relating to the transmission of the air to consider the actual volume of the air during the transmission, or usually either at the beginning or at the completion of the transmission. As air in transmission soon attains the temperature of the pipe and its surroundings, its temperature need not generally be taken into account as affecting the volume. The volume of free air transmitted may be assumed to be directly as the absolute pressure or the number of atmospheres to which the air is compressed. Thus if the air transmitted be at 75 lbs., or 6 atmospheres, the actual volume of free air transmitted will be six times the volume given in the body of the table. For comparing cases of transmission the linear velocity of flow is generally adopted, and is the more convenient form of statement. It is generally considered that for econom-

ical transmission the actual velocity in main pipes should not exceed 20 feet per second. It would be well if more attention were given to the capacities of the distributing-pipes employed. In practice it often occurs that while the main pipe is large enough for the transmission, the smaller pipes, or hose, through which the air is finally transmitted to the individual machines are too small, and velocities as high as 50 feet per second are not infrequently met with.

Compressed air has usually to be transmitted a greater or less distance from the compressor to the place where it is used, and in computing the cost or the economy of operations in which compressed air is employed it becomes necessary to consider the friction of the air in the pipes, and the power lost in overcoming it. Upon this point some very extravagant and widely erroneous ideas have been quite generally disseminated. The popular impression is that great power losses are inseparable from the transmission of air through pipes. The facts are quite different from this. It seems to be certain that power may be transmitted by compressed air for considerable distances with less loss than by any other known means. We cannot do anything for nothing, and of course there is some loss of power in the transmission of compressed air, but in general practice thus far, unless the piping system has been outrageously bad and inadequate, the losses by transmission have not been worth considering. The distances traversed have usually not been great enough to make the loss a serious one, or at all to be compared with the losses of power through the heating of the air in compression, or through its loss of volume by the cooling of re-expansion when the air was finally employed. But as compressed-air practice develops we want longer lines, and then the

question of transmission rises to greater importance. We want to convey air long distances for the purpose of employing unused and now worthless water-powers. We want long lines of piping for supplying street-cars with the means of propulsion and for the general distribution of power and the general application of compressed air to its multifarious uses in large cities. We want to convey natural gas from the wells where it flows to the towns and cities, where it may be used to the best advantage.

When we come to look up the formulas to depend upon for our computations, we do not find any that are satisfactory and reliable. The best that may be said of the best of them, and that with caution, is that they are approximately correct, but we know that they must be in error in some particulars. The available data in this line are meagre and chaotic, inconsistent and self-evidently unreliable. It is perhaps too much to expect that close accuracy can ever be attained in these computations. There are too many factors in the case, and a little variation in any one may make a great difference in the result. A statement of the friction in the case of compressed air flowing through a pipe involves at least all of the following factors: Unit of time, volume of air, pressure of air, diameter of pipe, length of pipe, and the difference of pressure at the ends of the pipe, or the head required to maintain the flow. Neither of these factors can be allowed its independent and absolute value, but is subject to modifications in deference to its associates. The flow of air being assumed to be uniform at the entrance to the pipe, the rate of flow is not constant for the whole length of the pipe, nor indeed for any point but the beginning of it. As the air may be said to carry in itself, in its elasticity, its own means of propul-

sion, some of which it is using as it goes along, it is constantly losing some of its pressure, and its volume is therefore constantly increasing. If the quantity of air entering the pipe is to continue to flow through it, the linear velocity of flow must be constantly accelerated on account of this increase of volume. This also modifies the use of the length of the pipe as a constant factor. It would be very natural to assume, as in the formulas in general use it is assumed, that if a certain head were sufficient to maintain a certain flow for a given length of pipe, double the head would be sufficient for double the length. But that could not be so; for in the second length all the head that propelled the air through the first length has disappeared, and the volume is now greater through the loss of that pressure, and the velocity is now greater, and it must require more additional head for the second length than was required for the first. So of the other important factor, the diameter of the pipe. The actual area of section, or the apparent capacity of the pipes, is, of course, directly as the square of the diameter, but the volume of air transmitted for given length and head will not be in any such ratio. The surface resistance of the interior is proportionately much greater in the smaller pipe. While the area is as the square of the diameter, the periphery is directly as the diameter. The greatest distance of any portion of the air from the periphery being less in the smaller pipe, the viscosity of the air counts for more. For volumes in proportion to the areas of the pipes a 1-inch pipe will require for a given length more than three times as much head as a 2-inch pipe.

Then besides the fluctuating values of these fickle factors there is that other factor, unrecognized in our compu-

tations, but arrogantly assertive in practice—the condition of the pipe itself. The actual diameter of wrought-iron pipe, especially in the smaller sizes, is different from the nominal diameter. Some pipe is smooth, and some has seams and blisters. The pipe may be straight, or it may be crooked and have numerous elbows. Everybody knows that elbows are unpleasant things to encounter. Tables have been published of the effect of elbows in retarding the flow of compressed air. One of these tables, copyrighted, is before me, and from it I gather that eight or ten 1-inch elbows have a retarding effect equal to one length of pipe, so that if the table is to be believed, elbows are not as obstructive as they are commonly supposed to be. If we say, without copyright, that a single elbow is equal to a length of pipe we will be nearer right than the table.

No table or formula can make allowances for foreign substances or obstructions in the pipe, and it seems unnecessary to call attention to the necessity of thoroughly blowing out the pipe before it is put to use. Long lines of pipe are sometimes laid through a variety of rough country, and before the pipe is coupled up many things get into it that have no right to be there. In pipe-lines for transmitting natural gas it has been the practice before the pipes were put to service to turn on the full pressure of the gas and blow out the pipe. The pressure in such cases is often as high as four or five hundred pounds to the inch, and under such a force the pipe is usually quite effectually cleared, stones, sticks, leaves, squirrels, rats, and snakes having sometimes been ejected.

And here it might be proper to say a word about the importance of the unimportant. It is the general practice of pipers when running a line of pipe for air or water or

steam to put the white lead, or whatever may be used as a cement for the joint, into the coupling or elbow or other "female" fitting, wiping it around and filling the threads with it, and then when the end of the pipe or the "male" thread is screwed into it, none of the cement is left upon the outside, and a neat and clean-looking job is the result. The trouble in the case is that the job would not be so neat and cleanly looking if it could be seen from the inside. As the pipe end is screwed into the fitting the cement that does not remain in the threads—and not much of it does remain in the threads—is carried forward before the end of the pipe, and, when the pipe is screwed home, remains there and hardens, often rising above the inner surface of the pipe enough to cause a considerable stricture or reduction of pipe area. Now, if instead of this the cementing material is put upon the male thread when the pipe is screwed in, all that is not taken up by the threads remains on the outside of the pipe, instead of inside; and although it does not look as neat as by the other practice, and entails the labor of wiping off the joint, we know that the inside of the pipe is clear.

FORMULA FOR THE FRICTION OF AIR IN PIPES.

D = Diameter of pipe in inches;
L = Length of pipe in feet;
V = Volume of air delivered in cubic feet per minute;
H = Head or difference of pressure required to overcome friction and maintain the flow.

$$H = \frac{V^2 L}{10{,}000 D^5 a};$$

$$V = \sqrt{\frac{10{,}000 D^5 a H}{L}};$$

$$D^5 a = \frac{V^2 L}{10{,}000 H};$$

$$L = \frac{10{,}000 D^5 a H}{V^2}.$$

VALUES OF a FOR DIFFERENT NOMINAL DIAMETERS OF WROUGHT-IRON PIPE.

1 ″	.35	3 ″	.73	8″	1.125
1¼″	.5	3½″	.787	10″	1.2
1½″	.662	4 ″	.84	12″	1.26
2 ″	.565	5 ″	.934	16″	1.34
2½″	.65	6 ″	1	20″	1.4
				24″	1.45

It will be noticed that the values of a for the 1¼″ and the 1½″ pipes are not consistent with the values given for the other sizes of pipe. This is in recognition of the actual diameters of those two nominal sizes of wrought-iron pipe, which are 1.38″ and 1.61″ respectively.

FIFTH POWERS OF D.

1 ″	1	3 ″	243	8″	32,768
1¼″	3.05	3½″	525	10″	100,000
1½″	7.59	4 ″	1,024	12″	248,832
2 ″	32	5 ″	3,125	20″	3,200,000
2½″	97.65	6 ″	7,776	24″	7,962,624

Two or three examples are offered showing the application of the above formulas, although their use should be sufficiently evident to anyone capable of making the computations. The volume, V, is of course the actual volume of the air as it flows through the pipe under pressure, and not the volume of free air.

Say that we wish to transmit 1200 cu. ft. of free air per minute at 75 lbs. gauge pressure, or 6 atmospheres, through a 4″ pipe for 1000 ft., what additional pressure or head will be required to overcome the friction and maintain the flow of air? 1200 cu. ft. of free air ÷ 6 = 200 cu. ft. at 75 lbs. gauge. Then

$$H = \frac{200^2 \times 1000}{10{,}000 \times 1024 \times .84} = 4.65 \text{ lbs. head required.}$$

Having a 4″ pipe 1000 ft. long and a head of 5 lbs., what volume of air will be transmitted per minute?

$$V = \sqrt{\frac{10{,}000 \times 1024 \times .84 \times 5}{1000}} = 207.38 \text{ cu. ft.}$$

The volume of free air in this case will be dependent upon the pressure during the transmission. If this 207.38 cu. ft. were under a pressure of 60 lbs. gauge, or 5 atmospheres, the volume of free air would be 207.38 × 5 = 1036.9 cu. ft. If the pressure were 90 lbs. gauge, or 7 atmospheres, the volume of free air would be 207.38 × 7 = 1451.66 cu. ft.

Having 2000 cu. ft. of free air per minute compressed to 100 lbs. gauge, through what length of 6″ pipe may it be transmitted, losing 10 lbs. pressure in the transmission? Here the terminal pressure would be 90 lbs. gauge, or 7 at-

mospheres, and the volume would consequently be 2000 ÷ 7 = 285.7 cu. ft. Then

$$L = \frac{10{,}000 \times 7776 \times 1 \times 10}{285.7^2} = 9526 \text{ ft.}$$

Having 1500 cu. ft. of free air per minute to transmit a distance of 2000 ft., the air being at 80 lbs. gauge, and wishing to deliver it at 75 lbs., what should be the diameter of the pipe? Here we have a head of 5 lbs., and the air is delivered at a pressure of 6 atmospheres, so that the delivery-volume will be 1500 cu. ft. ÷ 6 = 250 cu. ft. Then we have

$$D^5a = \frac{250^2 \times 2000}{10{,}000 \times 5} = 2500 \text{ in.}$$

This is the only case where the fifth power can possibly make any trouble for us, and by referring to the following table of values of D^5a for the regular sizes of pipe the necessity of struggling with the fifth root is avoided.

VALUES OF D^5a.

1 ″.....	.35	5″.....	2,918.75
1¼″.....	1.525	6″.....	7,776
1½″.....	5.03	8″	36,864
2 ″.....	18.08	10″.....	120,000
2½″.....	63.47	12″.....	313,528
3 ″.....	177.4	16″.....	1,405,091
3½″.....	413.2	20″.....	4,480,000
4 ″.....	860.2	24″.....	11,545,805

Our answer above being 2,500, we note that it is less than 2,918.75, the value of D^5a for 5″ pipe, so that a 5″ pipe will be a little larger than is required by the conditions, and

is the size of pipe that should be used. We may verify this by assuming a 5″ pipe and computing what head would be required, the other conditions remaining unchanged.

$$H = \frac{250 \times 2000}{10{,}000 \times 3125 \times .934} = 4.28.$$

As this head is somewhat smaller than 5, the given head, this also shows that a 5″ pipe would be a trifle larger than would be required by the conditions, while a 4″ pipe would be much too small.

The pressures to which air is compressed do not in practice always, or generally, occur in even atmospheres. The following table, VIII, will be found convenient in ascertaining the actual volume of compressed air at any given pressure if the volume of free air is given, or *vice versa.*

TABLE VIII.

TABLE OF THE RELATIVE VOLUMES OF COMPRESSED AIR AT VARIOUS PRESSURES.

Gauge Pressure.	Volume of Free Air for 1 Cu. Ft. at given Pressure.	Volume at given Pressure for 1 Cu. Ft. of Free Air.	Gauge Pressure.	Volume of Free Air for 1 Cu. Ft. at given Pressure.	Volume at given Pressure for 1 Cu. Ft. of Free Air.
0	1	1	45	4.061	.2462
1	1.068	.9356	50	4.401	.2272
2	1.136	.8802	55	4.74	.2109
3	1.204	.8305	60	5.08	.1967
4	1.273	.7861	65	5.421	.1844
5	1.34	.7462	70	5.762	.1735
10	1.68	.5951	75	6.102	.1638
15	2.02	.4949	80	6.442	.1552
20	2.36	.4236	85	6.782	.1474
25	2.7	.3703	90	7.122	.1404
30	3.041	.3288	95	7.462	.1340
35	3.381	.2957	100	7.802	.1281
40	3.72	.2687			

The second column in the above table gives the volume of free air for 1 cu. ft. of compressed air at a given pressure, and this value may be used as a multiplier for any number of cubic feet at given pressure to ascertain the equivalent volume of free air.

Having 550 cu. ft. of air at 80 lbs. pressure, what will be the volume of free air?

$$550 \times 6.442 = 3548.1 \text{ cu. ft.}$$

The third column in the table gives the volume of air at any given pressure for 1 cu. ft. of free air, and this value also may be used as a multiplier for any number of feet of free air to ascertain its volume after compression to a given pressure.

If we have 1750 cu. ft. of free air, what will be its volume when compressed to 65 lbs.?

$$1750 \times .1844 = 322.7 \text{ cu. ft.}$$

The following table, IX, of the head or additional pressure required to overcome friction in the flow of air in pipes has been computed by the preceding formulæ. It is believed to be correct and reliable as far as it goes, and should be a convenience in many cases of compressed-air transmission for rock drills and similar uses. A table covering all the various pressures and conditions in general practice would be too voluminous to offer here.

As we have before remarked, so many conditions may combine to modify the specific case of transmission that both the formulas and the table here given can have only a rough and general application and a provisional usefulness until something better appears.

TABLE IX.

TABLE OF HEAD OR ADDITIONAL PRESSURE REQUIRED TO DELIVER AIR AT 75 LBS. GAUGE PRESSURE THROUGH PIPES OF VARIOUS SIZES AND LENGTHS.

1-inch Pipe.

Linear Velocity in Feet per Sec.	Volume of Free Air per Min.	Length of Pipe in Feet.						
		50	100	150	200	300	500	1000
12.72	25	.245	.4944	.735	.98	1.47	2.45	4.9
25.44	50	.981	1.962	2.943	3.924	5.886	9.81	19.62
38.16	75	2.23	4.45	6.68	8.9	13.35		
50.88	100	3.925	7.85	11.77	15.7			

1¼-inch Pipe.

Velocity in Feet per Sec.	Volume of Free Air per Min.	Length of Pipe in Feet.						
		50	100	150	200	300	500	1000
6.7	25	.0567	.1134	.1701	.2268	.3402	.567	1.134
13.4	50	.2268	.4536	.6804	.9072	1.3608	2.268	4.536
26.8	100	.9072	1.8144	2.7216	3.6288	5.4432	9.072	18.144
40.2	150	2.0412	4.0824	6.1236	8.1648	12.2472	20.412	

1½-inch Pipe.

Velocity in Feet per Sec.	Volume of Free Air per Min.	Length of Pipe in Feet.						
		50	100	150	200	300	500	1000
4.9	25	.0172	.0344	.0516	.0688	.1032	.172	.344
9.8	50	.0688	.1376	.2064	.2752	.4128	.688	1.376
19.6	100	.2752	.5504	.8256	1.1008	1.6512	2.752	5.504
29.4	150	.6192	1.2384	1.8576	2.4768	3.7152	6.192	12.384
39.2	200	1.1008	2.2016	3.3024	4.4032	6.6048	11.008	22.016

TABLE IX.—(*Continued.*)

2-inch Pipe.

Velocity in Feet per Sec.	Volume of Free Air per Min.	Length of Pipe in Feet.						
		50	100	150	200	300	500	1000
6.369	50	.0192	.0384	.0576	.0768	.1152	.192	.384
12.738	100	.0768	.1536	.2304	.3072	.4608	.768	1.536
19.107	150	.1728	.3456	.5184	.6912	1.0368	1.728	3.456
25.476	200	.3072	.6144	.9216	1.2288	1.8432	3.072	6.144
31.845	250	.48	.96	1.44	1.92	2.88	4.8	9.6
38.214	300	.6912	1.3824	2.0736	2.7648	41.472	6.912	13.824

2½-inch Pipe.

Velocity in Feet per Sec.	Volume of Free Air per Min.	Length of Pipe in Feet.						
		100	200	300	400	500	1000	2000
8.163	100	.0428	.0856	.1284	.1712	.214	.428	.856
16.326	200	.1712	.3424	.5136	.6848	.856	1.712	3.424
24.489	300	.3859	.7718	1.1577	1.5436	1.9295	3.859	7.718
32.65	400	.6848	1.3696	2.0544	2.7392	3.424	6.848	13.696
40.81	500	1.072	2.144	3.216	4.288	5.36	10.72	21.44

3-inch Pipe.

Velocity in Feet per Sec.	Volume of Free Air per Min.	Length of Pipe in Feet.						
		100	200	300	400	500	1000	2000
5.659	100	.01647	.03294	.04941	.06588	.08235	.1647	.3294
11.318	200	.06588	.13176	.19764	.26352	.3294	.6588	1.3176
16.977	300	.14823	.29646	.44519	.59292	.74115	1.4823	2.9646
22.636	400	.26352	.52704	.79056	1.054	1.3176	2.6352	5.2704
28.295	500	.41175	.8235	1.233	1.647	2.058	4.1175	8.235
56.59	1000	1.647	3.294	4.941	6.588	8.235	16.47	

TABLE IX.—(*Continued.*)

3½-inch Pipe.

Velocity in Feet per Sec.	Volume of Free Air per Min.	Length of Pipe in Feet.						
		100	200	300	400	500	1000	2000
10.661	250	.04202	.08404	.12606	.16808	.2101	.4202	.8404
21.32	500	.16808	.33616	.50424	.67232	.8404	1.68	3.36
31.98	750	.37817	.75634	1.1345	1.5127	1.89	3.78	7.56
42.64	1000	.67232	1.344	2.0169	2.6893	3.36	6.72	13.446
53.3	1250	1.0505	2.101	3.1515	4.202	5.25	10.505	21.01

4-inch Pipe.

Velocity in Feet per Sec.	Volume of Free Air per Min.	Length of Pipe in Feet.						
		100	200	300	400	500	1000	2000
15.91	500	.08074	.16148	.2422	.3229	.4037	.8074	1.615
23.86	750	.18166	.3633	.545	.7266	.908	1.816	3.633
31.82	1000	.32296	.6459	.969	1.29	1.615	3.229	6.459
39.77	1250	.5046	1.009	1.514	2.018	2.523	5.046	10.092
47.73	1500	.7267	1.4534	2.18	2.907	3.633	7.267	14.534

5-inch Pipe.

Velocity in Feet per Sec.	Volume of Free Air per Min.	Length of Pipe in Feet.						
		500	1000	2000	3000	4000	5000	10000
10.18	500	.11896	.2379	.4758	.7137	.9517	1.189	2.379
20.36	1000	.4758	.9517	1.9033	2.855	3.8067	4.758	9.516
30.54	1500	1.0706	2.1413	4.2826	6.424	8.565	10.706	21.41
40.72	2000	1.9033	3.8067	7.613	11.42	15.227	19.033	
50.90	2500	2.974	5.948	11.896	17.844	23.79	29.74	

TABLE IX.—(*Continued.*)

6-inch Pipe.

Velocity in Feet per Sec.	Volume of Free Air per Min.	Length of Pipe in Feet.						
		500	1000	2000	3000	4000	5000	10000
14.18	1000	.1786	.3572	.7144	1.0716	1.428	1.786	3.572
21.27	1500	.4018	.8037	1.6074	2.411	3.215	4.018	8.037
28.36	2000	.7144	1.4288	2.857	4.286	5.715	7.144	14.288
35.45	2500	1.116	2.232	4.465	6.697	8.93	11.162	22.325
42.54	3000	1.607	3.215	6.43	9.645	12.86	16.075	32.15

8-inch Pipe.

Velocity in Feet per Sec.	Volume of Free Air per Min.	Length of Pipe in Feet.						
		1000	2000	4000	6000	8000	10000	15000
15.91	2000	.296	.592	1.184	1.776	2.368	2.96	4.44
19.88	2500	.4626	.925	1.85	2.775	3.7	4.62	6.939
23.86	3000	.6661	1.332	2.664	3.996	5.329	6.66	9.99
31.82	4000	1.184	2.368	4.737	7.105	9.474	11.842	17.76
39.775	5000	1.85	3.701	7.402	11.103	14.8	18.505	27.757

10-inch Pipe.

Velocity in Feet per Sec.	Volume of Free Air per Min.	Length of Pipe in Feet.						
		2000	4000	6000	8000	10000	15000	20000
10.18	2000	.1844	.3688	.5532	.7376	.922	1.383	1.844
12.73	2500	.288	.5763	.8644	1.1526	1.44	2.161	2.88
25.46	5000	1.15	2.305	3.458	4.61	5.763	8.644	11.5
38.19	7500	2.59	5.186	7.78	10.37	12.967	19.45	
50 92	10000	4.61	9.22	13.83	18.44	23.05		

TABLE IX.—(*Continued.*)

12-inch Pipe.

Velocity in Feet per Sec.	Volume of Free Air per Min.	Length of Pipe in Feet.						
		2000	4000	6000	8000	10000	15000	20000
8.84	2500	.11075	.2215	.332	.443	.5537	.83	1.1075
17.68	5000	.443	.886	1.329	1.772	2.215	3.322	4.43
26.52	7500	.9967	1.993	2.99	3.987	4.98	7.47	9.96
35.36	10000	1.772	3.544	5.316	7.088	8.86	13.29	17.72
44.2	12500	2.769	5.538	8.3	11.07	13.84	20.74	

CHAPTER XIII.

THE UP-TO-DATE AIR-COMPRESSOR.

THE principal thing to be said of the up-to-date air-compressor is that it is not up to date. It would be difficult even now, and notwithstanding the improvements which we are told have been made in air-compressors in the last few years, to find the one that embodies the best knowledge of the time, or that in actual performance accomplishes what should be expected of it with our present knowledge of the practical conditions of economical compression. The standard of performance for a single-stage air compressor may be taken to be: a cylinderful of free air at normal temperature compressed isothermally, and all delivered to the receiver, by an apparatus involving no losses through friction, and we should expect to realize a nearer approach to that standard than we do. We should in the first place be able to ascertain what is actually done in economical air-compression to-day, and if any one undertakes that he will find that it is no simple task. The catalogues of air compressor manufacturers are interesting in this connection, and the alleged indicator-diagrams contained in them are worthy of study. I have learned from them, if nothing else, to respect the wisdom of the builder who does not allow the diagrams from his steam- and air-compressing cylinders to be seen.

While, as we know, air-compressors are built and running with the air-compressing cylinders placed tandem to the

steam-cylinders, the piston rod of the steam-cylinder being continued into the air-cylinder and transmitting all the power required for compression directly to the compressing piston, and with a friction loss of only 5 per cent between the steam-cylinder and the air-cylinder, there are indicator-diagrams published in builders' catalogues that show very different results. In one set of diagrams, bearing every evidence of genuineness, but published without data, the ratio of the air-cylinder M.E.P. to that of the steam-cylinder is .633, a loss of over 36 per cent in power alone, saying nothing of the other inevitable losses. In another catalogue a set of alleged indicator-diagrams is given with some accompanying data, and with a ratio of air-card to steam-card of .818, a loss of 18 per cent. A diagram from an air-compressing cylinder, published by another manufacturer, shows the air-admission line above the atmosphere-line for almost the entire length of it, as though the air would rush into the air-cylinder with alacrity when the pressure was higher within the cylinder than outside of it! Still another builder, commenting in his catalogue upon this phenomenon, says that the fact that the air-admission line is above the atmosphere-line proves that his rival's piston leaks. I have in my possession still another indicator-diagram from a compressing cylinder with newly patented valves, and in which the air pressure in the cylinder at the beginning of the compression-stroke is ten pounds above the atmosphere, although the cylinder is filled with free air at each stroke and the entire compression is done in that one cylinder. And so it goes. We may say that the air-compressor builders are living upon the ignorance of their customers, or we may say that the blind are leading the blind, as may seem most correct for the individual case.

Of all the steam-actuated air-compressors in existence the one showing the very worst results, as far as economy of steam for the service performed is concerned, is the air-compressor used upon locomotives for operating the air-brakes. To compress a given volume of free air to a certain pressure the "air-brake pump" uses nearly ten times as much steam as would be required in the best air-compressors of the day for the same service. The air-brake pump, however, is the one compressor whose extravagant waste of steam is condoned by the circumstances surrounding its employment. There are more than 30,000 of these pumps in use, a number greater, perhaps, than that of all other air compressors combined, not counting those that are used for beer. While the wastefulness of this pump is fully conceded, its persistent use for air-brake service is completely vindicated. The pump is very simple and always ready, which is an important point, and the steam used to operate it upon the locomotive is mostly steam that otherwise would be blown off by the pop safety-valve. The pump is usually worked when stops are made at stations or when running down grade, and if the pump used much less steam it would generally mean not that so much steam was saved, but that the safety-valve would have so much more to do. Various styles of air-brake pumps have been devised showing a much better economy, but they have been successively abandoned for the established pump. It is only when the air-brake pump is used for the purpose of a general compressed-air supply, as it quite frequently is in railroad shops, that its extravagance is to be condemned. In such cases no language can be too severe to characterize the folly of it. That the air-brake pump can be used with profit and satisfaction to supply

compressed air for general use speaks highly of the value of the air.

As a mechanical curiosity, and as exhibiting a great achievement of ingenuity, a set of indicator-diagrams from an air-brake pump are here reproduced, Fig. 20 being from

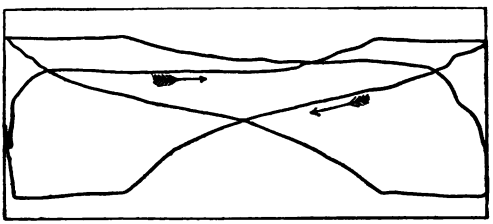


Fig. 20.

the steam-cylinder and Fig. 21 from the air-cylinder. The steam-cylinder diagrams are so different from the familiar cards of the ordinary steam-engine cylinder that it has been thought best to place the arrows upon them to indicate the direction of motion. They would look more natural to the

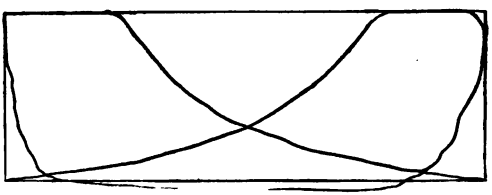


Fig. 21.

general steam engineer if he could be allowed to read them in the reverse way. It will be noticed that the steam pressure in the cylinder is low at the beginning of the stroke, corresponding with the low resistance in the air-cylinder, and that the steam pressure rises with the progress of the stroke, and at the end of it the cylinder is full of

high-pressure steam, while that steam has done much less work than would be due to the dead pressure of that volume of steam, saying nothing of the additional power that could have been developed by using expansively. This is evidently a more wasteful application of steam even than in the direct-acting pump for water. This distribution of steam, however, accomplishes the designed purpose of approximately equalizing the steam pressure to the resistance, and the air-brake pump is thus enabled to dispense with the crank-shaft and all which it implies.

Under any arrangement that has been invented for using steam economically the pressure in the steam-cylinder during the earlier part of the stroke is at its highest, and decreases generally to nothing, or nearly nothing, at the end of the stroke. In opposition to this the resistance in the air-cylinder at the beginning of the compression-stroke is very low and increases as the piston advances, and at the latter part of the compression-stroke this resistance is considerably higher than the force of the steam that is driving the piston. To keep the compressor in motion it is not enough that the mean effective pressure upon the steam-piston for the whole stroke shall exceed the mean effective resistance against the air-piston plus the friction of the entire apparatus. The force and resistance must be equalized in some way to keep up the movement, and various devices have been employed for this purpose. The usual reliance at the present time is upon the weight of the reciprocating parts and heavy fly-wheels, and it is doubtful still if there is anything that is in all respects to be preferred. A novel and ingenious arrangement for accomplishing this desired object has lately been brought out by one of the air-brake companies, not so much, it is understood, for air-

brake service, as for general use in air-compression. The two air-cylinders of this compressor are horizontal and single-acting, and they together form the foundation for the entire compressor. While they are together equal in free air capacity to a double-acting cylinder of the same diameter and stroke, they are in other respects quite different, as the pistons have movements independent of and always different in speed from each other, except momentarily at a point near the middle of each stroke. Above the air cylinders is placed the steam-engine, which forms a part of and which actuates the air-compressor. The engine comprises the usual elements of the horizontal steam-engine—the steam-cylinder and its piston, the cross-head, connecting-rod, crank-shafts, fly-wheels, and the mechanism of the valve motion. Short connecting-rods attached to the cross-head give motion to two compensating levers with changing fulcrums, and through these levers power is transmitted to the air-compressing pistons; and with a uniform movement assumed for the cross-head a continually decreasing movement is given to each air-piston for its compression-stroke. At the beginning of either stroke of the steam-piston the fulcrum of the equalizing lever is above the middle of it, and the air-piston moves faster than the steam-piston. At the latter part of the stroke of the steam-piston the fulcrum of the lever is nearer its lower end, and the air-piston then moves much slower than the steam-piston. The indicator-diagrams Fig. 22 show the practical operation of this compressor. The upper diagram, from the steam-cylinder, shows the steam at 100 pounds cut-off at four tenths of the stroke. The dotted line of the diagram shows the effect of the steam pressure for the stroke as modified by the weight and inertia of the reciprocating

parts. The lower diagram, from the air-cylinder, exhibits

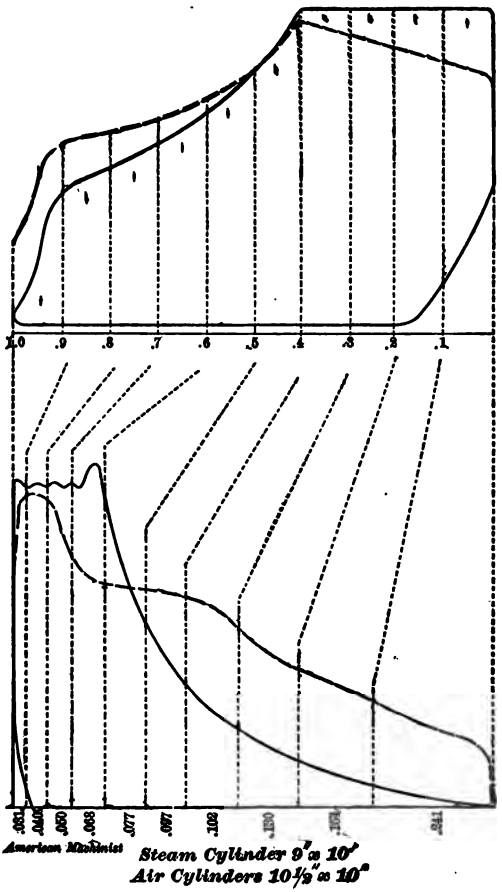


Fig. 22.

the operation of compressing free air up to and delivering

it at 100 pounds pressure. The dotted lines in this diagram show the resultant force from the steam-piston as transmitted by the action of the compensating lever to the air-piston. It is evident that the work required of the fly-wheel in this case is less than in the ordinary steam-engine, while in the common air-compressor it is much greater. These cards show the friction of the compressor to be high, the ratio of the air to the steam-cylinder diagram being .75, a loss of 25 per cent from this source alone.

The full sponsorial and patronymic appellation of the most pretentious member of the air-compressor family to-day is the Corliss Cross-Compound Condensing Compressor. It may be called the Five C's. The "cross" is not practically as good as the tandem, but commercially the alliterative effect is valuable. The Corliss feature is one of the most valuable adjuncts for selling the compressor, but has nothing to do with operating it. The Corliss engine, as everybody knows, is designed to maintain a uniform speed under a varying load. The cut-off, controlled by the governor, is changed as the load changes and because the load changes. The air-compressor is required to maintain a constant air pressure when there is a varying demand for the air, and this varying demand means of course, and can only mean, a varying speed of operation, so that to take a fully equipped Corliss stationary engine and to attach an air-cylinder tandem to the steam-cylinder, or, if a double or compound engine, to attach an air-cylinder tandem to each steam-cylinder, the propriety of the arrangement must be very evident to those who can see it. All computations upon the efficiencies of air-compressors have been based upon the assumption of constant work under the best conditions. When it is recognized

that no compressed-air service is uniform in its demands, then the sacrifice of ideal conditions that the varying demand entails becomes quite an important factor in determining the ultimate economy of the system. How a compressor is governed is a very pertinent question for the economist. I cannot afford to go into it here, but I may say that nine tenths of all the air-compressors in use, not including the air-brake pumps, have no governors, and the governing devices employed upon most of the others are crude, unsatisfactory, and generally disgraceful.

Where large air-compressing plants are to be established for continuous service, a much higher ultimate economy can be attained than where the plant required is not so extensive. It is best to use a number of units for the work of compression instead of one or two large compressors. Air-compression offers little or no opportunity for the storage of power or for doing any work in advance, as may be done by a water-pump and reservoir. The receivers used in connection with air-compressors will not usually hold more than the compressor can deliver in one minute, so that if the demand for the air fluctuates it must be met by the speed of delivery at the compressors, and not by a change of reservoir supply. Air-compressors, like simple steam-engines, have their conditions of speed, pressure, etc., that secure the best economy; and where a plant consists of a number of units, all in operation, it will usually be more economical to let most of them, or as many as possible, run steadily at their best, and to do the governing or equalizing of the work by one or two of the compressors rather than by all of them. The more extensive the air-compressing plant may be or the more extensive the use of the air compressed the more uniform the demand may be expected to be.

CHAPTER XIV.

COMPRESSED AIR *VERSUS* ELECTRICITY.

THE title of this chapter is adopted in deference to the prevalent idea of the relations of these two power-transmitters. To my thinking the *versus* should be read as lightly as it is possible to read it, for there is in fact but little antagonism or competition between compressed air and electricity, and there is little likelihood that in practice there ever will be. Neither of them is a power-transmitter pure and simple, as a wire rope may be said to be, but each is capable of performing other functions, and the power-transmitting capabilities of each, in combination with their other individually peculiar lines of usefulness, open for each a distinct and separate field, which neither can fill for the other. The same is true of some of the other power-transmitters. They each have their special fields of usefulness and adaptability which neither of the others could fill as well, if at all.

Of late the gas-engine has been coming rapidly to the front as a valuable agent in the development, transmission, and distribution of power, and it has its enthusiastic advocates who are ready to predict that before long it is to supersede every other motor over a field that is practically boundless. But upon looking over the field a little farther and listening to another group of enthusiasts it soon appears that not the gas-engine but the oil-engine is *the* coming

motor, and not only is it the coming motor, but it has already come, and is driving out the electric and gas and other motors, and the steam-engine also, in England and Germany and elsewhere in Europe, and it must soon do so also with us in the United States. But as we look into the operating conditions under which these several agencies may find employment we soon learn that each of the several motors is most applicable under conditions of its own, and that neither can do all that either of the others can do. Gas and oil, of course, develop power as the steam-engine does, while compressed air and electricity can only transmit power that originates elsewhere. But with the development and transmission of power the usefulness of gas ("producer" gas) or of oil ends, while with air and electricity power-transmission is not their only function. Electricity has the vast field of illumination, in which it reigns supreme; compressed air has no one application to compare in magnitude and importance with that of electric lighting, but it has a vast number of duties which are all its own, and which electricity cannot touch. The use of compressed air has been slow of development, and is still backward, but at this writing I am able to enumerate two hundred distinct and established uses of compressed air, and in more than 90 per cent of those uses electricity is absolutely inapplicable, and in the remainder, which form a field more or less open to other agencies besides either air or electricity, the air generally has the advantage. Turn to the last chapter of this little book, wherein some of the uses of compressed air are enumerated, and see all those that come under the first letter of the alphabet and judge where the competition with electricity comes in. In our list of the applications of compressed air some of the other

letters of the alphabet develop a larger enumeration than the first letter, and the use of air for operating motors, or for producing rotary motion in general, or for performing any of the functions of the steam-engine, is not included. Referring to the portion of the list under the letter *A*, it will be noticed that the only applications of air that compete with electricity are the air-brake and the air-hoist or the air-jack. The electric brake in competition with the air-brake is anything but a success, and it is not worth further mention. Even upon electric cars the air-brake is an absolute necessity for safety, and hundreds of lives have been sacrificed in our city streets because it has not been used. The air-jack also has the field to itself, and electricity is "not in it." In the field of general hoisting air and electricity divide the work, and the line of service done by each is generally distinct from that performed by the other. There are establishments where they are thoroughly familiar with the uses and capabilities of electricity, operating, for instance, electric travelling cranes, and yet which use compressed air in numerous places throughout their works for hoisting, and where for the special services required electricity would have no chance at all. Where the direct-acting vertical hoist can be used, or the air-cylinder, either vertical or horizontal, with multiplying sheaves and a wire rope, it is, of course, preferable to electricity with its spinning motor-shaft, its drums and gearing. In the general work of hoisting as carried on at the Armour Packing Company's vast establishment electricity could not possibly do the work that the air does. The wonderful capability of standing ready for instant use at full power and without cost for maintenance for long periods of time seems to be possessed by compressed air alone. It is pre-eminently adapted to

uses that call for constant alertness, as in the switch and signal service and in the air-brake, and in the air-hoist it stands at its post day and night ready to give a lift the instant it is called upon.

In the lines of service to which electricity and compressed air seem to be, perhaps, equally applicable, and where they could compete with no apparent disadvantage to either, it is to be regretted that circumstances seem invariably to defeat a fair comparison. In driving pumps a very fair test could be instituted of the relative merits of each, and of the losses in the use of each, as power-transmitters, and it happens that in this very work of pumping we find some striking illustrations of what might be termed the constant bad luck accompanying the air, or the malignant opposition of circumstances to any fair exhibition of its powers. Compressed air, by its very accommodating attitude, by its very applicability to widely varying conditions, is constantly placing itself in a false position before the community and showing itself at a disadvantage. It is able to accept conditions that enable it to make an unseemly and unjust exhibition of its powers, yet which entirely exclude electricity from any such depreciatory performance. The pump that can be operated by electricity can be operated equally well by compressed air, the air-motor taking the place of the electric motor, either of them producing rotary motion; and with suitable connecting gearing and with the pump mechanism unchanged one would have as good a chance as the other, and under those conditions the air could be made to do better than the electricity.

Electricity seems to be making advances more rapid than ever before in its employment for railway traction. It

drives the horses from the surface roads, and is now beginning to supersede the steam locomotive. Perhaps all do not realize that this is the triumph after all of the steam engineer more than of the electrical engineer. Electricity is demonstrating not so much its superiority as a power-transmitter, but is simply showing the ultimate economy of generating power in large central plants, even if the means of distribution is a wasteful one, and accompanied by features that are insurmountably objectionable. The extending use of electricity as a railway motor is an argument also for compressed air, for it is able to take full advantage of the economy in centralized power development, and we are in the way to see very soon some practical demonstration of its abilities in this field. In railroad service, as in everything else, compressed air has been heretofore unfortunate, and its advocates and would-be promoters have wasted time and opportunity in developing minute economies in the air-motor which were not needed to enable it to compete with the best in the field. It may be regarded as certain that whatever gain may be shown in the employment of electricity for traction its establishment is by no means a final solution of any question except of the economical generation of power, and that electricity has nothing to do with.

Has any one called attention to the fact that one of our most prominent and perplexing political questions is entirely and indisputably the product of compressed air? Can electricity claim to have contributed any prominent factor in determining the course of parties or in shaping the destinies of the nation? What if compressed air should be found to hold the balance of power and the deciding voice in the selection of a future President of the United States?

This is the actual situation, and not an absurd or exaggerated statement of it. The only political function attained by electricity is that of public executioner. Electricity and compressed air stand to each other as the masked and nameless headsman upon the one side and Warwick the King-maker upon the other. The silver question of the day, whichever side of it we may find ourselves on, is entirely the outgrowth of the increased output of silver, and that, no one can deny, is what the air-driven rock drill has accomplished. The precipitation upon us of this perplexing question may have been a work of questionable beneficence, but the power that could achieve it is not to be treated lightly.

CHAPTER XV.

THE THERMAL RELATIONS OF AIR AND OF WATER.

In all of our operations with compressed air, either in its compression, its storage and transmission, or in its final application to whatever purpose, the temperature of the air at any time, and the effect of raising or lowering its temperature by whatever means, are always important facts to be considered, and it will be well for us as early as possible to fix in our minds some general ideas upon the subject. The thermal relations of water are so different from those of air that by contrast a knowledge of the one may be made to enforce our knowledge of the other. The fact also that the effects of heat upon water are accepted as standards of heat measurements makes it necessary for us to know something about them.

Say that we apply a given quantity or unit of heat to a pound of water, raising its temperature 1 degree; how much air would be equally heated, or have its temperature raised 1 degree, by the same unit of heat? A cubic foot of air at atmospheric pressure—"free air"—and at 62 degrees weighs .076 pound, and a pound of air therefore in volume equals $1 \div .076 = 13.158$ cubic feet. A pound of water is 27.7 cubic inches, and the ratio of volumes of water and of air of equal weight will be about 1 : 821. But, pound for pound, it takes less heat to raise the tem-

perature of air 1 degree, or any number of degrees, than is required to raise the temperature of water the same number of degrees. The specific heat of water being 1, that of air is only .2377, so that 13.158 cubic feet ÷ .2377 = 55 cubic feet, and this 55 cubic feet of free air is to be compared with 1 pound, or 27.7 cubic inches, of water.

There is a means of fixing the thermal relations of air and water in the mind's eye so that they may not be easily forgotten. A common-sized glass tumbler, not quite full, holds a half-pound of water. A cubical box measuring 3 feet each way, or say a large dry-goods box, holds, of course, a cubic yard, or 27 cubic feet, which is, nearly enough, a half of our 55 cubic feet, so that the dry-goods box full of air and the tumbler full of water represent quite closely the volumes of air and of water that will be equally heated by equal units of heat. The approximate ratio of volumes will be 1 : 3431, and the ratio of the sides of two cubes representing the two volumes will be 1 : 15 +. The isometric projection of the two cubes here shown (Fig. 23) may convey and impress the relations better than the figures can do it.

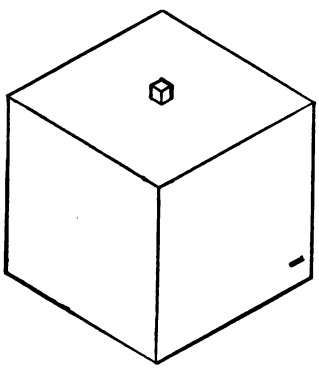


Fig. 23.

It is to be remembered that in the transmission of heat either to or from air or water—that is, whether heating or cooling them, or whether cooling or heating any bodies in thermal communication with them—the above ratios will prevail. Those whose attention is called for the first time

to the phenomena accompanying air-compression or expansion cannot fail to be struck with the great changes of temperature that ensue coincidently with either operation, but the actual heat represented by these changes is usually overestimated, although circumstances that should check the exaggerated estimate are also at hand. If the body of the air-compressing cylinder and the cylinder-heads are properly water-jacketed, the temperature of the air delivered is considerably lower than it would be if there were no water-jacketing, but, at the same time, the perceptible heating of the water in the jacket, by which the partial cooling of the air is effected, proceeds quite slowly, showing that the actual quantity of heat abstracted from the air by that means is not great. So also when the heated compressed air flows through pipes for some distance, the rapidity with which its temperature approaches that of its environment is another evidence of the small amount of heat actually carried by it. Still we hear constantly of the wonders of heating or cooling that are to be done by compressed air—wonders that never fully materialize with a more extended experience. In the Pohle "air lift pump" (which is not properly a pump, as it has absolutely no moving or working or wearing parts, but which is a very valuable application of compressed air direct for raising water from bored wells, and where the air is discharged upward into the submerged end of a vertical water-pipe, the air entering the pipe, distributing itself through the water, and rising with it, expanding as it rises) it is claimed that the expansion of the air while in contact with the water cools the water. We may say that the expanding air certainly does cool the water, and we may also say that it certainly does not cool the water more than a fraction of a single degree.

Where an establishment is equipped with a permanent compressed-air plant, for operating hoists, jacks, presses, and isolated machines of all kinds, it is a simple matter to rig up an arrangement for cooling the drinking-water for the employés. Take a 1¼″ pipe 100 feet long (50 feet might be long enough), place it horizontally, and connect one end of it to the compressed-air supply, with a suitable cock to control the escape of the air. Leave the other end of the pipe open and enclose the whole of the pipe, after passing the air-admission cock, in a thick non-conducting covering. If nothing better is at hand, take plenty of paper, and wind it on spirally layer after layer, covering the whole pipe. Then lead a ⅜″ water-pipe into the open end of this horizontal released air-pipe, and let it come out by a tee or otherwise at the other end of the air-pipe, and the whole apparatus is provided. The air in this case should be thoroughly cooled and have all its suspended water discharged before its release in the cooling-pipe.

A touching spectacle in all our large cities are those melancholy monuments of a futile philanthropy, its public drinking-fountains. The motive that prompts their erection is worthy of all respect. Much money has been expended upon them with the best of intentions, but with the poorest of results. They can nowhere be said to be a success, for they do not accomplish what they propose to do. They offer the cup to the thirsty lip, but it is practically an empty cup, for it does not hold what we want. Who wants to drink warm water? The most costly and artistic of fountains is nowhere, in the thought of the hot and thirsty crowd, in competition with a bucket of cold water and an old, rusty tin dipper. The instinctive call of humanity for cold water to drink is so absolutely universal

that it must be correct, and should be more adequately provided for.

Our cities are constantly doing more and more for the comfort and well-being of all the people. To all of us life is more worth the living by reason of our co-operation and our collective helpfulness. Amid all that is designed to make our cities more attractive and more desirable to live in, is there any possible material thing that can be suggested more to be desired, more proper to do, more promising of universal good, than to make it possible for every man, woman, and child to have always at hand a drink of *cold* water? Does not compressed air make it possible? The establishment of a general compressed-air service in any city might be gloriously celebrated by the establishment of a cold-water fountain.

If anyone does undertake to cool drinking-water by the use of compressed air, we may expect to hear that it takes a great quantity of air to cool a little water, which is just about what I have been writing above. The case, however, in the matter of cooling by compressed air is not nearly as bad as I seem to make it appear. The actual heat represented by any change of temperature in air compressed to a pressure of several atmospheres is of course greater than for air compressed to only 1 atmosphere, or free air, as we call it, and directly in proportion to the respective absolute pressures. With air at 75 lbs. gauge, or 6 atmospheres, the same change of temperature in either heating or cooling would indicate a transfer of six times the amount of heat that would be indicated by the same heating or cooling of free air. The sudden release of air compressed to 6 atmospheres and at 62° before the release would cause a theoretical fall of temperature of over 200°,

and if this air were in communication with water that required to be cooled but 20°, this would give the air a considerable advantage. In the case of the Pohle air lift pump, cited above, where the volume of water would probably be as great as that of the compressed air in contact with it, the cooling effect of the expanding air could be but slight, as before stated.

CHAPTER XVI.

THE FREEZING UP OF COMPRESSED AIR.

THE most familiar and the most constantly reiterated objection to the use of compressed air is its well-known habit of "freezing up" under certain conditions, and too many who have not sufficiently investigated the subject have regarded this freezing-up of the air as an insurmountable and fatal objection to its use for purposes for which it would seem to be otherwise eminently adapted. By "the freezing up of the air," as the expression is commonly used, —although, of course, it is never the air that freezes,—we understand a deposition of moisture, more or less rapid, upon the sides of the pipes or passages that convey the air, and its accumulating and freezing there until the area of the channel is materially reduced, the proper flow of the air prevented, and the operation of the air-motor or other apparatus seriously impeded or stopped entirely. This phenomenon may easily occur and has frequently occurred in the use of compressed air. The earlier experimenters in this line all encountered it, and most of them on account of it at once dropped compressed air as a practicable power-transmitter, and the freezing up of compressed air has remained a formidable bugaboo among otherwise intelligent mechanics to this day.

The best way to do in a case like this is first of all to have a good look at it all around in broad daylight. It

would seem to be worth while to get together where we can see them the principal facts of the case, so that we may be able to understand the conditions under which the freezing up occurs, whether it must always accompany the use of compressed air, and, if not, the combination of conditions under which all danger of freezing up may be successfully avoided.

Intelligent mechanics to maintain their up-to-date intelligence must be wide-awake and fully informed, and such should know that in these days compressed air is widely used not only without freezing up, but also without any reheating or other special device for preventing it. Compressed-air locomotives, probably hundreds of them, are constantly used, in mines and elsewhere, without any reheating of the air and without freezing up, and the builders of those locomotives will absolutely guarantee them to do it every time. Rock drills by the thousand and pumps and hoisting-engines without number are run by compressed air without reheating it and without freezing up.

It must be evident that for freezing up to occur two things are essential, and neither alone could have any effect toward producing such a result. The free moisture must be present and accumulating, and the temperature of the air where the freezing up is to occur must be below the freezing-point. The moisture alone can cause no trouble as long as the temperature continues high enough. It will simply be carried along with the air and will be discharged with it. So, too, a low temperature of the air in the passages at any time will not freeze up anything as long as there is no free moisture present to be frozen.

We may say generally that air always contains moisture. Its capacity for moisture is determined by the combined

conditions of pressure and temperature to which it is at the time subjected. Changes either of pressure or of temperature immediately change the capacity of the air for water, and, supposing the air to be saturated with water, whenever, either through increase of pressure or through decrease of temperature, the capacity of the air for water is reduced, the excess of water is dropped. At constant temperature the capacity of air for water seems to be inversely as its absolute pressure. By another mode of stating this it may be said that the capacity of the air for water is independent of its pressure or density. It is so stated by parties who have an eminent right to speak upon the subject; and the statement is correct if rightly understood, but it is apt to be misleading. At uniform temperature a given volume of air implies a capacity for a certain weight of water, whether the air be at a pressure of 1 atmosphere or of 100 atmospheres; but if the air has been compressed from a pressure of 1 atmosphere to a pressure of 100 atmospheres, or if its volume has been reduced from, say, 100 cubic feet to 1 cubic foot, or in that proportion, its capacity for water has really been reduced to one hundredth of its original capacity; and if the air before the compression was saturated with water, then after the compression, and after it has fallen to its original temperature, it must have dropped somewhere during the operation $\frac{99}{100}$ of the water that it originally carried.

At whatever pressure the air may be changes of temperature immediately affect the capacity of the air for carrying water. The water-carrying capacity of the air seems to be as sensitive to temperature as to pressure. We know very distinctly the general fact that the hotter the air the greater its capacity for moisture; but there seem to be little satis-

factory data as to the quantity of water that will be carried by compressed air under different conditions of temperature. The absence of such data, however, need not seriously cripple us in our quest.

In the operation of air-compression the heating of the air, and the increase of water capacity thereby, seems to keep pace with and to compensate for the reduction of water capacity consequent upon the reduction of volume, and we never hear of any trouble from liberated water in the compressing cylinder, but after the air leaves the compressor the water begins to make itself known, and all the world hears of it. As the air leaves the compressor it is usually quite hot, and even at the high temperature the air is usually saturated, or nearly saturated, with water. As the air cools the water begins at once to be released, and before it is thoroughly cooled considerable water is generally deposited. Changes in the meteorological conditions, or in the original humidity of the air as it enters the compressing cylinder, of course change the amount of water precipitated by the air after compression, and all who have experience with compressed air find that on this account the air carries and deposits more water at some times than at others.

Many amateurs and experimenters have encountered trouble from the freezing up of the air on account of taking the air immediately from the compressor, before it has been completely cooled, or, if cooled, by neglecting to drain off all the liberated water from the pipes before using the air. The experience thus obtained embodied an important lesson if it could have been learned, but the lesson has been too often misread, and the interpretation of the freezing up phenomenon has been an incorrect one. When an air-motor or an engine driven by compressed air "freezes up,"

usually by the choking of the exhaust passages, the general impression among mechanics is that the water is precipitated by the air at the moment when the freezing occurs; but the fact usually is that the water is deposited in the pipes by the air before the motor or engine is reached, and the water is then carried along as entrained water by the friction of the air, and when the temperature of the air falls below the freezing-point, on account of its expansion in the cylinder or at the exhaust, the water, being present and in contact with the cold air, is of necessity frozen.

The general practice of the day in the compression and transmission of air does not seem to make adequate provision for disposing of the water deposited by the air while cooling. As the air leaves the compressor it is usually quite hot, and even at the high temperature it is saturated or nearly saturated with water. As the air cools it begins at once to lose its capacity for water, and some of the water is dropped and continues to be deposited as long as the air continues to cool. In connection with the compressor, and usually quite near it, a receiver or reservoir of considerable capacity is provided, the most important function of which is, or is assumed to be, that of collecting the water that may be precipitated by the compressed air. In too many cases this receiver fails of its mission, or only partially collects the water from the air, because, if the compressor is working constantly and rapidly, as it usually does, the air goes through the receiver and out of it and into the pipe-line before it has time to cool. The air after compression will not drop all of its water until it is thoroughly cooled, and the cooler it gets the greater will be the quantity of water liberated; and when the air, still under full pressure, has reached the lowest pressure attainable, means should then

be provided for collecting the liberated water, or it must, of course, be carried along in the pipes to make trouble by freezing up where the air is used, and where the air expands and cools while doing its work or upon its release. With a receiver near the compressor, and with hot air passing through it, and a pipe-line long enough to completely cool the air before it is used in rock drill, air-motor, pump, or other constantly running machine, and with no provision for disposing of the water in the pipe, we should expect to hear of the machines freezing up. Cases are quite common where a second receiver placed at the farther end of a pipe-line has effectually cured the freezing up by removing the congealable liquid.

A few years ago many air-compressors for driving rock drills were in use in the United States—a large number of them upon the Croton aqueduct—which cooled the air during compression by the injection of jets of water into the air in the compressing cylinder. Compressors of this style are not now built by any firm in the United States. The cylinders were found to wear out quite rapidly, the compressors could not be run as fast as the dry compressors, and for other similar reasons they did not pay. They did, however, deliver the compressed air decidedly cooler than the compressors now in use deliver it, and it is not surprising that it should be claimed by rock-drill runners, and probably correctly, that those old injection compressors, with the water intimately mingling with the air during the compression, still furnished drier air, and consequently air less liable to "freeze up," than the more modern dry compressors furnish.

In the process of wood-vulcanizing, for preserving wood by cooking the sap in the wood, the material to be treated is enclosed in tight cylinders and subjected to an air press-

ure of 150 pounds. The air is specially heated and made to circulate around and among the wood and absorb the moisture that may be liberated from it, so that it is essential to the process that the air should be as dry as possible, and the paradox occurs that to secure *dry* air the *wet* or injection type of compressor is employed.

I know a certain iron mine which has two air-compressors side by side, each connected to deliver the compressed air through the same receiver and the same pipe to the rock drills in the mine. One of the compressors delivers its air at a temperature considerably below that of the air from the other compressor, say from 50° to 100° lower, neither of the compressors being of the injection type, and it is constantly noted that the men in the mine operating the drills can immediately tell which compressor is running by the relative humidity of the air supplied. The compressor which delivers the coolest air of course delivers the driest air.

When the air is completely saturated with water, contact with water will not make it any wetter. The water in the injection compressor did not wet the air, for it was as wet as it could be; and as that water enabled the compressor to deliver the air at a lower temperature than the dry compressor would deliver it, the air, simply because it was cooler, actually emerged from the compressor bearing less moisture than the air emerging at the same pressure, but at a higher temperature, from the dry compressor. If no means were provided for draining the surplus water from the air, except, in either case, the receiver located near the compressor, the cooler air passing the receiver would carry the less amount of water into the pipe and through it; but if, in each case, after the air had traversed the pipe a sufficient distance to have become thoroughly cooled another receiver or drainage chamber had been provided, there is

no reason why, after emerging from the chamber, the air in each case being at the same pressure and temperature, the one should carry any more water than the other. To get rid of all trouble from water in the air, and the possible freezing of it, care should be taken that when the air passes a point where it is still at full pressure and has reached its lowest temperature, such means of drainage shall be provided that none of the liberated water shall be carried into and along the pipes beyond that point.

The possible freezing up that we have been contemplating thus far along in this chapter is where water is present by deposition from the compressed air, and where a low temperature is caused by the expansion of the air, and the freezing of the water ensues by contact. Another mode of freezing up is experienced where the freezing is accomplished not by the air that has been compressed, but by the external atmosphere. In the winter if compressed air at low temperature, but still above the freezing-point, saturated with water, as it is pretty sure to be, and with the pipe thoroughly drained to a certain point, has then to pass for some distance through a pipe exposed to a freezing atmosphere, it cannot fail to deposit some water, and the freezing of the water so deposited may soon choke the pipe. I have encountered cases of this kind more than once, notably in one of the largest chemical works of the country, where the pressure of the air is employed in lifting and transferring acids so that they may not be exposed to metallic contact. The air-pipe was carried through the extensive works and from building to building, and in some places between the buildings where exposed to the extreme cold of a sharp winter it was choked up by the accumulation and successive freezing. The only apparent lesson in this case is to protect the pipe from frost. A pipe conveying compressed air and

exposed to a freezing atmosphere is quite sure to choke up. The deposition of the water may proceed slowly, but if the low external temperature continues, the accumulation will eventually reduce the air-channel, or even close it entirely. This result is, of course, chargeable to the weather, and not to the innate frigorific malignity of the compressed air.

The pressure at which the compressed air is transmitted, and eventually used, has an important bearing upon the question of its freezing up in use. If the air is transmitted only short distances, and at comparatively low pressures the probabilities of freezing up are much greater than if high pressures are employed and if the distance of transmission is at least sufficient to allow a thorough cooling and drainage of the air while under the full pressure. In the use of low-pressure air for any service, of course a larger volume of free air is used to furnish any given power, and the larger volume of air implies the presence of a greater quantity of water in suspension, and the lower pressure employed affords less opportunity, or no opportunity, for extracting the water, and, as a fact of experience, most of the freezing-up trouble that is encountered is from air that is used at comparatively low pressure.

There are many considerations, which I need not enumerate here, to commend the use of air at high pressures, and not the least among those considerations is the practical immunity from freezing up that is thereby secured. This may be readily understood. Say that air is compressed to 1000 pounds gauge, or, say, 70 atmospheres, either that smaller pipes may be used for long-distance transmission, or that smaller receivers may be used for the storage of air upon a street railway motor, and say that the air is admitted to the motor at 100 pounds pressure. If while the air is at 1000 pounds it is thoroughly cooled and drained, it is evi-

dent that when that air is expanded to 100 pounds, and has been allowed to regain its normal temperature, if the air was just saturated with moisture when at 1000 pounds pressure and normal temperature, when it has expanded to more than eight times its former volume it can be only one eighth saturated, and no water can be deposited by it in expanding from 100 pounds downward, and however low the temperature may fall there can be no freezing up.

A valuable use of compressed air is for the transmission of packages or mail matter through suitable tubes from one station to another. In this pneumatic transmission service some trouble has been experienced in the winter from the accumulation of ice in the pipes. As the pressure employed is low the freezing up might be prevented by compressing all the air to a pressure considerably higher than required and cooling and draining it while under that higher pressure. Then after passing a reducing valve to the low pressure for use the air would be dry and could not deposit moisture to be frozen.

Compressed air is often used in caissions for bridge piers and kindred uses where the compressor is so near the caission that the air in transmission does not become as cool as it should be, and the men find the warm atmosphere very oppressive and are unable to do as much work as should be expected. The service pipes are sometimes cooled by passing them through water, but even then the air in the caissons is warmer than it should be for vigorous work. In this case also if the air were compressed to a pressure, say, 20 or 30 pounds higher than required, then cooled as well as possible by passing the pipes through cold water, and after that admitted to the caisson through a pressure-reducer adjusted to the desired pressure, it would then be cool enough, or it might even be made cooler than required.

CHAPTER XVII.

REHEATING COMPRESSED AIR.

WHILE air at low temperature has a comparatively small cooling effect upon water or upon whatever may be in contact with it, the fact inversely applied is of advantage in the use of compressed air for power-transmission. It requires comparatively little heat to raise the temperature of air rapidly. It is well known that after the transmission of compressed air to the point where it is to be employed a considerable saving in the cost of the available power is effected, theoretically at least, by reheating the air before it is used. While many have called attention to this matter in various ways, few have given us any definite and reliable data regarding it. Little is generally known as to the actual economy of such a practice, or of the conditions under which it is practicable.

It may easily be shown that where a certain volume of air has been compressed to a given pressure, and has by transmission or storage resumed approximately its normal temperature, if that air is then reheated and thereby expanded, the additional volume of compressed air resulting from the expansion is produced by an expenditure of heat much lower than the original volume of compressed air was produced for, and by a much lower expenditure of heat than is required to produce an equal volume of steam. The actual figures in the case, all theoretical, are as follows :

Weight of 1 cu. ft. of steam at 75 lbs gauge = 2089 lb.

Total units of heat in 1 lb. of steam at 75 lbs from water at 60° = 1151.

Total units of heat in 1 cu ft of steam at 75 lbs. = 1151 × 2089 = 240.44.

To produce by compression through a steam-actuated air-compressor, 1 cu. ft of compressed air at 75 lbs. and 60° about 2 cu. ft. of steam of the same pressure are required, or the heat-units employed in producing 1 cu. ft of compressed air will be about 240.44 × 2 = 480 88 heat units as the thermal cost of 1 cu. ft. of compressed air at the above temperature and pressure The temperature and volume of the air as it leaves the compressor will be considerably higher than the figures here assumed, but as the air is invariably stored for a time, or is transmitted through pipes to a distance, between its compression and its ultimate employment, it may be said to always return to its normal temperature before it is used, so that, whatever we may have at the compressor, the air as it is delivered to the motor, or whatever apparatus may be operated by it, will have cost, as above stated, 480.88 heat-units for 1 cu. ft at 75 lbs The difference in the thermal cost of any volume of compressed air thus produced by mechanical compression and the cost of any additional volume of air that may result from the subsequent reheating of the air is very striking.

The weight of 1 cu ft. of free air at 60° = 076 lb

Weight of 1 cu. ft. of compressed air at 75 lbs and 60° = 456

Units of heat required to double the volume of 1 lb. of air at 60° = 123 84.

Units of heat required to double the volume of 1 cu. ft.

of compressed air at 75 lbs. and 60° = 123.84 × .456 = 56.47.

Cost of 1 cu. ft. of superheated compressed air at 75 lbs. compared with the cost of 1 cu. ft. of compressed air as produced by ordinary compression:

$$480.88 : 56.47 :: 1 : .1174.$$

Here we see that the cost in heat-units of the volume of air produced by the reheating is less than one eighth of the cost of the same volume produced by compression. Upon this showing the matter is certainly worth looking into, because if there is such a possible opening for the economical application of heat to the development of power, we ought to know it and avail ourselves of it.

The operation of reheating compressed air is correctly so termed. It is, in fact, a case of doing work over again, or of replacing in the air heat that has been lost by it in previous operations. It must be confessed that the presumption is all against our finding much profit in this direction There are not many places in life where it pays to do our work a second time There is, as we have seen, practically no air-compression without heating the air by the operation, and there is no transmission of air after compression without its cooling to very near its original temperature If the air could go immediately from the compressing cylinder into the motor cylinder, where it does its work, without losing any of its heat, it would have the same effective power as it would have after long-distance transmission and cooling and reheating, and without the additional cost of that reheating. While we are saying in all good faith that there is little loss of power in the transmission of compressed air

to considerable distances, and that the difference in the pressure of the air at the two ends of a long pipe necessary to overcome the friction and maintain the flow is but small, and that it is, to a great extent, compensated for by the increased volume at delivery, the fact still is that there is a great loss of power in the transmission of the air, if we reckon from the moment when compression ceases on account of the inevitable cooling of the air. Still this loss is not properly chargeable to the transmission, for no matter how far the air may be transmitted the cooling is all accomplished before the air has travelled very far if the pipes are of proper size. Supposing air to be transmitted ten miles, it must be conveyed with considerable rapidity if it does not get down to normal temperature before the end of the first quarter of a mile.

As the volume of air under any constant pressure varies directly as the absolute temperature, it follows that to double the volume by heating the air its absolute temperature must be doubled. The air being at 60°, its absolute temperature will be $60 + 461 = 521$, and double this will be $521 \times 2 = 1042$, the absolute temperature required. This by the thermometer will be $1042 - 461 = 581°$. As this is the temperature that is required for the air when delivered into the motor, and actually beginning its work, it will be necessary, on account of the ease and rapidity with which it cools, to heat the air considerably higher than this theoretical temperature. It is one thing, and an easy one, to heat the air, while it is a very different and a very difficult thing to keep it hot. To avoid all loss of heat it would be necessary, not only to keep the pipe which conveyed the air constantly hot, but also the cylinder in which

it was used, or it would be cooled before it began to do its work. In one case within my experience, where compressed air was reheated, and its absolute temperature was increased at the heater 38 per cent, and where, of course, its theoretical increase of volume was the same, the actual increase of power realized was only 12 per cent. In this case the air was transmitted after the reheating about 20 feet, the pipe was not covered, and no precautions were taken to prevent loss of heat by radiation. The volume of air transmitted was sufficient to develop between 20 and 30 horse-power. The theoretical temperature required to double the volume of compressed air at 60° being 581°, the actual temperature required at the heater under the most favorable conditions in order to have a double volume of air available *in* the motor will not be less than 800°, and this is a temperature that it is practically impossible to employ and maintain, and we may as well give up all thought of doubling the volume of compressed air by reheating it and of realizing the promised economy of the operation.

If instead of doubling the volume we only attempt to increase it by one half, or 50 per cent, which it is practicable to do, the required theoretical temperature (absolute) will be 521 + 50 per cent = 782, and 782 − 461 = 321°, the sensible temperature required. Adding enough to this to allow for the intermediate cooling, the actual temperature required should probably be not less than 450°. The temperature of the air before the reheating being assumed to be 60°, the increase of temperature will be 450° − 60° = 390°. As we saw above that it required 56.47 heat-units to raise the tempeature of 1 cu. ft. of compressed air at 75 lbs. gauge pressure from 60° to 581°, the actual increase of tem-

perature being $581 - 60 = 521$, it follows that to raise the temperature 390° will require:

$$521 : 390 :: 56.47 : 42.27.$$

Then if the first cubic foot of compressed air costs 480.88 heat-units for its compression, and if the additional half of a cubic foot produced by reheating costs 42.27 heat-units, the total cost of $1\frac{1}{2}$ cu. ft. under the reheating system will be $480.88 + 42.27 = 523.15$, and the cost per cubic foot at this rate will be $523.15 \div 1\frac{1}{2} = 348.76$ heat-units. The relative cost in heat-units of 1 cu. ft. of compressed air produced by compression alone, and of a cubic foot resulting from compression and reheating, will be:

$$480.88 : 348.76 :: 1 : .72.$$

From this it appears that the gain by reheating compressed air sufficiently to increase its effective volume 50 per cent will be 28 per cent. The more fair and correct way to state this, however, will be to reverse it:

$$.72 : 1 :: 1 : 1.38.$$

We may say, then, that the total fuel applied with the reheating system will yield 38 per cent higher results than are to be realized without the reheating. This seems to be very near the maximum that can be attained in the way of economy by reheating *dry* compressed air.

It is not always, nor, indeed, often, that the reheating of compressed air is practicable or possible. In a valuable report upon compressed-air appliances by a committee of the Master Car-Builders' Association, 1894, they say: "It was reported by the manufacturers of air-appliances that superheated compressed air used in air-lifts, jacks, engines,

etc., increases the efficiency fully 50 per cent, but your committee was unable to make tests or to procure reliable data, etc." The "manufacturers of air-appliances," quoted by the committee, either were not responsible for their words or they did not know what they were talking about. Bearing in mind the facility and rapidity with which heated air in transmission loses its heat, it is idle to think of ever heating compressed air except for continuously running motors, and then by heaters very close to the motors. In Paris, where 25,000 horse-power is employed for general compressed-air service, the air in some instances is used to run engines that were formerly run by steam, the original boiler that supplied the steam for the engine being retained as a heater and reservoir for the air. That is all right, and wherever any motor or engine is to be run without interruption a heater for the air should certainly be employed; but at the end of this volume is a list of two hundred different and distinct uses of compressed air in not one of which would it be practicable or anything but a losing operation to try to heat the air. In the United States at the present time there is probably not one case in a thousand where compressed air is employed and where one cent of profit could be realized from reheating the air. It is to be regretted that American compressed-air practice is not so far developed, or developed upon such lines, as to make the economy of reheating the air before its use more readily and generally available. When, by and by, compressed air comes to be used for what we may term legitimate power-transmission, and is employed to drive small motors and motors not so small with the established functions of the steam-engine, then the reheater will find its field of usefulness.

In connection with this topic it is hoped that the accompanying diagrams, Figs. 24 and 25, will be of some interest and value. Fig. 24 shows the increase of volume accom-

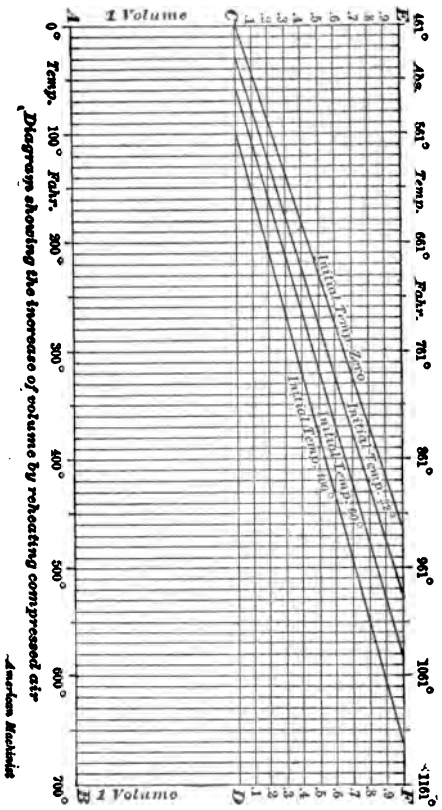


Fig. 24. Diagram showing the increase of volume by reheating compressed air

American Machinist

panying the heating or reheating of compressed air. The air is assumed to be heated from the several initial temperatures of 0°, 32°, 60°, and 100°, the pressure remaining constant during the operation represented. The relative

volume at any temperature is indicated by the height of the vertical line corresponding with that temperature, the height from *AB* to *CD* representing one volume, and each

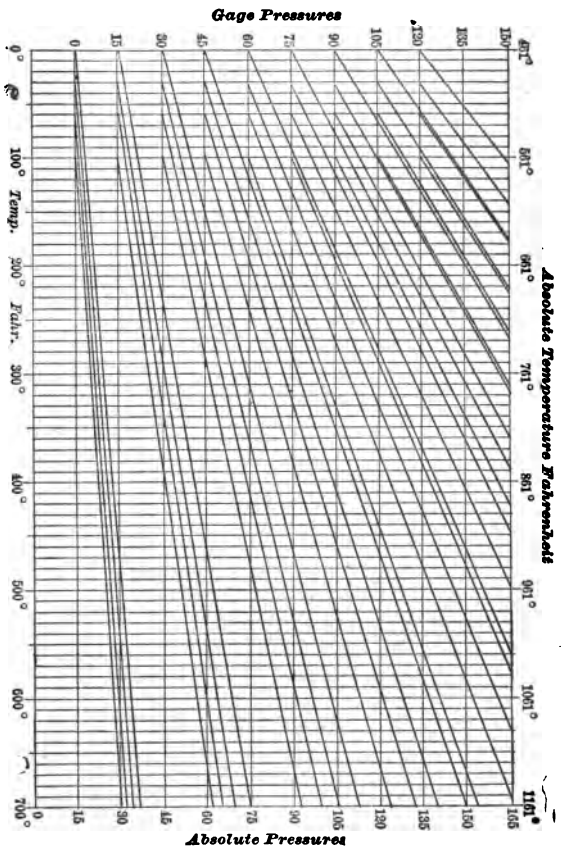


Diagram showing the increase of pressure by reheating compressed air.

Fig. 25.

horizontal line above that indicating, successively, an additional one tenth of volume. When the line *EF* is reached, the original volume is doubled. Figures below the base-line *AB* indicate the sensible temperatures

Fahrenheit, and the figures above the upper line indicate the corresponding absolute temperatures.

Fig. 25 shows the increase of pressure only caused by the heating of compressed air, the volume being constant. The air is assumed to be heated, as in Fig. 24, from the several initial temperatures of 0°, 32°, 60°, and 100°, and also from a number of different initial pressures. The pressures are indicated by the several horizontal lines, the vertical distance between any two adjacent lines representing approximately 1 atmosphere. The figures at the left of the diagram indicate the gauge pressures, and the figures at the right the absolute pressures. The temperatures are indicated as in the previous diagram.

CHAPTER XVIII.

COMPRESSED AIR FOR PUMPING.

THE air-compressor owes its modern development to the demands of the rock drill, in its various forms and applications, more than to any other single cause. The largest builders of air-compressors for general use first engaged in their manufacture to supply the air to the rock drills that they were building. All of the rock drills in all of the mines, and in every tunnel that is being driven, and in every shaft that is being sunk, we may say, are and apparently must be driven by compressed air. Nobody seems to inquire, and nobody knows very clearly, whether or not the power employed in operating rock drills is applied economically or not. The conditions under which the drills are employed and the nature of their work are all inimical to economy. It is impossible to measure the actual work done by a rock drill. It is enough that their work pays, and that there is little annoyance or anxiety involved in keeping them going all right.

But, taking the mines as they run, the operating of the drills is only one of several uses of power in mining operations, and not the largest of these, although to some it may seem to be the most important. Hoisting, including haulage, and pumping, either of them, upon the average, requires more power than is required for the drilling. Good steam-engines at the surface may generally be employed

for the hoisting, and they do so well that we need not here trouble ourselves much about them. With the use of power for mine-pumping it is all very different. The pumps must generally be located where the water is, and, if steam is used to drive them, far away from the boiler plant; and it so happens that to-day probably the most wasteful use of steam to be found anywhere is to be found where mine pumps are operated.

This certainly ought not to be so. The operation of pumping is one of the most favorable ever found for the economical application of power. The marine-engine and the water-works pumping-engine divide the honors as examples of the highest economy in the wide range of modern engineering practice. The stationary engine, except under the most favorable conditions, does not equal their performance. The success of the marine-engine and of the pumping-engine is to be attributed to the one operating condition that they have in common, and that is not found elsewhere. They have constantly uniform work to do. The pumping of water from our mines should also be economically done, because in this service, almost as much as with the water-works pump, the height of the lift is practically constant and unvarying. It is not necessary to say how different is the actual result in the case of the mine pump. Waste of power and expense for repairs, and for duplicate machinery, are the natural and inevitable accompaniments of steam-pumping in deep or extensive mines. The trouble of course is principally in carrying the steam so far.

Everybody should know that steam need not be employed under such conditions. Compressed air stands ready to do this work and to do it more cheaply and more satisfactorily

than it can be done by any other means. It is to be confessed that air, where it has been employed for mine-pumping, has not by any means made as favorable an exhibit as it should have made, and has not made the progress that it should toward universal adoption for this service. The why of it is easily found.

Here is a practical example in the case of what is said to be the largest coal-producing mine in the United States. Of course they have a lot of pumping to do there, and of course they use for it the always handy steam-pump. In this mine the steam is conveyed to the pumps by one line about a mile, and by another line about a mile and a half. The steam condenses all along its journey, and with high pressure at the boilers there is low pressure, and often too low pressure, at the pumps. What starts from the boilers as steam is mostly water when it gets to the pumps, and they are operated by combined hydraulic and vaporous action, the simple steam-pump thus becoming what might be termed a diabolically reversed compound. The great feature of the American steam-pump is that it will actually go. That it will go in the mine makes it also go in the market. It is to be recorded to its credit (?) that it makes it possible to do what it should be impossible to do. And so we find in this mine eight of these pumps, in various grades of inefficiency, and the steam is carried a mile or a mile and a half to make them go. The steam leaks everywhere, the roofs are rotting and tumbling in under the combined action of the heat and the moisture, sometimes joints blow out or pipes break, men are scalded, passages are blocked, ventilation is stopped, gangs of repairers are constantly employed, but the troubles keep increasing. Something has

to be done about it. It will not do to use steam any longer here.

When it comes to this point it is very unfortunate that this is a coal mine. A little item in the cost of a plant to be installed will outweigh all considerations of fuel or of power economy. The decisions of coal-mine managers are therefore no suitable precedents for the miners who must feed their boilers with greenbacks. Electricity or compressed air, either of them, stands ready to take up this job of pumping, and get rid of this steam nuisance in the mine. But electricity has no chance here, because new pumps would have to be bought, and there would be also the wiring of the mine, while compressed air is so accommodating that it agrees to use the old pumps and the old pipes, and no one need doubt that the pumps will actually go. Compressed air is accordingly adopted, not upon its merits, but because it will not cost so much to put it in; and electricity is not permitted to make an unseemly exhibition of itself.

Few perhaps realize how peculiar, and, indeed, unique, have been the conditions under which electricity has been spread abroad. In every case where it has been employed in power-transmission its installation has involved an entirely new plant throughout, each end of the plant has been adapted to the other, and every detail to the whole, so that it has never been placed in a false position or shown at a disadvantage, as compressed air is almost invariably served. If electricity had secured a chance at this mine, putting in the new electrically-driven pumps, as well as the generators, and with everything new, consistent, and complete, it would, no doubt, have put on airs over the results accomplished, as compared with what compressed air has done in some

cases; but there would have been, after all, really no basis for comparison.

For supplying the compressed air instead of steam to this mine, an excellent compressor-plant is installed, a plant that any manufacturer might be proud of and might be pardoned for bragging about. The performance of these compressors is presumably as good as that of any compressors to be found to-day. But the air furnished by the compressors is to be used in those abominable steam-pumps. I have elsewhere expressed my disgust at, and protested against, the apparent indifference of the air-compressor builders as to the uses to which the air is put after it leaves the compressor, or as to whether the air is applied economically or not. Too often the explanation in the case is the same as in this case, completely exonerating the compressor builders. The conditions determining the adoption of compressed air for this mine are that the old pumps are to be used. Of course the compressor builders cannot afford to kill their business to save their ideals; they get a good job, and the compressors are put in to drive those pumps.

It is not known that any worse contrivance has yet been discovered, as far as power economy alone is concerned, than the common direct-acting steam-pump. There are enormous clearances to be filled at every stroke of the pump, without any compensation for the waste or any justification of its existence, except the very insistent one that the clearance is one of the conditions necessary to make the pump go, or is necessary when tired steam is used. Not the slightest advantage can be taken of the possible expansion of the steam or air. Too often the reverse of expansion occurs, and at the termination of the stroke the cylinder is filled to a higher pressure than was required to

make the stroke, and all the cylinderful to be immediately exhausted. This may be worse with a duplex than with a single pump, as either piston may reach the end of its stroke and the cylinder may then be overfilled with steam or air while it is waiting to have its valve reversed by the movement of the other piston. But it always happens, in addition to this, that the pumps are not proportioned to the work to be done, or that the several pumps are not all so proportioned that the same pressure will operate each of them. Where the pumps were driven by steam transmitted a long distance, it might have been well to calculate upon lower steam as the distance increased, and to plan the pumps accordingly, but there is no calculation of the kind undertaken. The pumps are simply bought ready-made, and they fit about as well as other ready-made goods. Take the published list of the pumps in the mine that we are talking about. The actual heads under which the several pumps are operated is given, and I have added 10 per cent to the pressures due to those heads, and the operating pressures required in the steam-cylinders of the several pumps are then as follows:

No.	1	2	3	4	5	6	7	8
Lbs.	32	28	10	31	39	23	37	32

No. 3 is a small pump and runs bu. a short time each day, and is not of much account to us. Nos. 4, 5, and 6, however, are the largest pumps employed, located near each other, and delivering under the same head. If the above are not the several pressures required, they must be nearly in these ratios, and they seem to complacently ignore the fact that all the pumps should be operated by approximately the same pressure, especially if compressed

air is used to drive them. The pump for which the lowest pressure is sufficient, running under throttle, is quite likely to fill its cylinder with air at the highest pressure before the exhaust occurs. Unless the piping is outrageously inadequate the air pressure will be practically the same throughout the mine. In this mine the pipe capacity is liberal, and it is safe to assume that the air pressure in the pipes supplying these eight pumps will not be found to vary more than 1 lb. or 2 lbs. at the most throughout the series.

At this writing, the air-plant having been in operation considerably over a year, I have the written word of the superintendent that its efficiency has not been to this day definitely ascertained. All of the pumps have not been operated at once except in emergencies. The most definite statement obtainable is that with the compressors at a certain speed six of the eight pumps are run at once, which tells us nothing, as we do not know the speed of the pumps. It would be a simple matter, when everything was going, and at any time agreed upon, to station a man at each pump and let him count the strokes, and this, in connection with the revolutions of the compressors, would tell us much. From a knowledge of all the available data in this case, and from some knowledge of similar cases, I am willing to hazard the assertion that not more than 20 per cent of the I.H.-P. at the steam-cylinders of the compressors is to be found in the weight of water delivered by the pumps.

Of course the arrangement as it stands is a great improvement over the use of direct steam at the pumps, and everybody is to be congratulated over the change. Not only is there an actual reduction in the total consumption of steam, where it is used in the cylinders of the air-compressors instead of in the cylinders of the pumps, but all of the

annoyance, delay, danger, and expense of the steam-distribution is avoided. That, with suitable pumps, a different air pressure in the pipes, and a consistent combination of machinery throughout, the same work could be done for one half of the fuel is not worth considering, for this is a coal mine, you know. But if the same work could have been done with one half of the boiler and compressor-plant, that would been worth considering even at a coal mine, and is deserving of much serious thought where the installation of additional plants is under consideration.

Something may of course be said upon the other side of this case, and toward shifting the responsibility for it. Mine managers are not pump experts. The attitude of the pump builders is similar to that of the compressor builders. They simply sell the pumps and they know little about how people may employ them, as I have been told by agents and salesmen of pump establishments. No special pumps are built to be operated by compressed air. There should be such pumps in the market, and compressed air should not be used with any thought of economy in the common direct-acting steam-pump. The pump should be a geared pump, and the air-motor should be an engine with a cut-off adopted to the pressure of air employed.

Right here seems to be offered a fine opportunity for comparison between electricty and compressed air for power-transmission. Pumping is a line of work that either may do, and with little apparent unfair advantage in the conditions. The same pumps that are being put in to be operated by electricity would be equally adapted to be operated by compressed air, by the substitution of an air-engine for the electric motor and an adjustment of the gearing to correspond, and a fair comparison of the results might be

made. In a Western town a pumping-plant has recently been installed to be driven by electricity. The pumps are bought by the town, and the local electric-lighting company undertakes to maintain and operate them, transmitting the current 2000 ft., for 4 cents per 1000 gals. delivered against a pressure of 60 lbs., which is about twenty times the fuel cost for the same work in the best pumping-engines of the day. Electricity might sublet this contract to compressed air for one quarter of the figure, and the air would be greatly inflated over its good luck in getting the job.

In the general work of pumping there is evidently a great field still to be occupied by compressed air. It is the natural power-transmitter, and incomparably the best, for mining operations; and as the mine pumping requires more power than the rock drills, more compressed air should be used in our mines for the pumping, while, as a matter of fact, probably not one quarter as much air is used, and steam or mechanical transmission of power is employed at great inconvenience and expense. A pressure of 6 atmospheres, which is very suitable for the rock drills, could also be used to good advantage for the pumps, and proper arrangements for cooling and draining the air would fully dispel all danger of freezing, which is the prevalent bugbear of compressed-air practice.

Besides the pumping for mines there is the constantly recurring problem of power-transmission for the water-supply of towns and cities, and compressed air is well adapted for such service. With a general compressed-air service established in our large cities the air would be ready to operate the thousands of pumps, now driven mostly by isolated hot-air engines, which supply the tanks upon the roofs of high buildings, or of buildings on ground too high for the established water-supply to reach.

CHAPTER XIX.

A LIST OF THE VARIOUS APPLICATIONS OF COMPRESSED AIR.

THIS list is intended to include only the direct applications of compressed air to specific uses, and not its employment in an air-motor, or where it takes the place or does the work of a steam-engine or other power-developer. The list is of course incomplete, as such a list must necessarily be, for the applications of compressed air develop faster than they can become generally known and recorded. A slight explanation of the way in which the air is used is given in a number of cases.

Acids, Raising or Transferring.—Compressed air is largely used for this purpose in chemical works, or where acids are handled in bulk or in large quantities and where contact with the metals cannot be allowed. Vessels containing the acid are subjected to a pressure of air inside them and above the acid, and the pressure of the air causes the acid to flow wherever the pipe may lead it.

Accumulator for Hydraulic Hoisting Service.—The compressed-air accumulator takes the place of the heavy weights long used for maintaining a uniform and constant pressure and regulating the supply of water necessary in operating hydraulic cranes, lifts, etc. The air, compressed to the pressure required to be maintained, is contained in an upright cylindrical vessel of considerable capacity. The water

rises and falls in the lower part of the vessel, and a considerable fluctuation of level is possible without great change in the air pressure. A float upon the surface of the water controls the movement of a duplex pump to maintain the required water-supply.

Aerated Bread.

Aerated Fuel.—A jet of compressed air vaporizes or atomizes crude petroleum in furnaces which have a wide application in the arts wherever great heat with perfect control is required, as in glass factories, brick or lime kilns, forges and metal works, etc. The system is also used for generating steam, but for that purpose is not generally cheaper than coal. Lamps using compressed air with oil in a similar way are much used for out-of-door work, also in rolling-mills, railroad yards, etc.

Aerating Molten Metal in the Bessemer Process.—This was a revolutionary application of compressed air, and of untold importance in the manufacture and in the promotion of the use of steel. The air is forced up through a mass of melted cast iron, burning out the carbon and in a few minutes converting the entire mass into steel, thus producing steel cheaper than iron.

Aerating Water.—The aeration of water is usually carried on in connection with its filtration, and is equally necessary in many cases to render the water wholesome and potable. Extensive works for the purpose are provided in connection with the water-supply of many towns and cities. The air is made to traverse a series of water-tanks, passing successively up through the contents of each, carrying off volatile and objectionable constituents and imparting the necessary oxygen.

Agitating Syrups in Sugar-refineries.

Air-brake.—The air-brake, in use upon all passenger trains, and also largely used for freight, puts the control of the train entirely with the engineer. Before the use of compressed air for this purpose the brakes upon each car were applied and released separately by individual brakemen upon steam-whistle signals from the engineer. The brakeman is discharged and the whistle is seldom heard. The air is compressed by an air-brake pump upon the locomotive, and there are over 30,000 of these air-brake pumps in use, a number greater, perhaps, than that of all other air-compressors together. The air-brake pump has begotten a great number of new applications of compressed air, especially in connection with the different departments of railroad service.

Air-brake upon Street Railways.—The value of the air-brake upon the steam-roads and the necessity for a quicker and more efficient brake for street-cars, now that the cable and the trolley have made them heavier and have increased their speed, are leading rapidly to the adoption of the air-brake for street-railway service. They air-compressing pump on the street-car is operated by a crank or eccentric upon one of the axles of the car.

Air, Dense, see Dense-air Refrigerating.

Air-hoist.—This term is used in contradistinction to the pneumatic crane, the crane generally employing drums and gearing or other complicated mechanism, while the movement of the hoist is simple, direct, and of limited range.

Air-jack.—Air-jacks are largely used in railroad shops and are a distinct outgrowth of the air-brake pump, the pump being always at hand or easily procurable with other railroad supplies, and may be readily piped up wherever it may be wanted. The jacks are more properly air-lifts, usu-

ally operating from below the load to be lifted. Many jacks are sunk in specially prepared pits under repair tracks for taking out wheels and axles. Portable jacks are in use which have wheels and handles like a barrel truck. Standing the truck up sets the lifting cylinder upon its base, and the jack is at once ready for work. The air pressure is supplied by an air-hose connected with a convenient branch upon the air-supply pipe. "Pulling down" jacks are made for pulling down defective sills upon freight cars.

Air-lift Pump.—The Pohle air-lift pump is not properly a pump, except that it is employed for raising water, and it has no working or moving parts of any kind. A vertical water-pipe, usually in a bored or artesian well, extends down some distance below the level of the water to be lifted, and at the lower end of it, which is open, a compressed-air pipe discharges the air upward into the column of water, and the mingled air and water rise and flow from the upper end of the water-pipe. The flow of water continues as long as the air is supplied. The pump gives excellent economical results and is highly commended.

Air-lifts, see Elevators.

Air-lock Doors.—The air-lock is used for the ingress and egrees of workmen and material to and from caissons, the excavating chambers of soft-ground tunnels, or wherever operations are carried on under air pressure. The lock is a chamber of sufficient size to receive two or more men at a time or a bucket of material. It is provided with two sets of doors and valves to admit or discharge the air. To enter the working chamber the outer door of the lock is opened, then the men enter the lock and this door is closed. A valve is opened admitting air from the working chamber until an equal pressure is attained in

the lock, when the inner door may be opened and the men admitted. The same operation occurs in the admission of material, and the process is reversed for egress. By a late improvement the outer doors of the air-lock are opened and closed by the pressure of the air acting upon pistons connected with the doors, and the locks are operated more rapidly than formerly, especially for the hoisting or lowering of material.

Applying Hose-couplings.

Armor, Diving, see Diving-armor.

Asphalt-refining, see Refining Asphalt.

Automatic Pump, see Ejector.

Automatic Fire-extinguisher.

Balloon, Water, see Raising Ships.

Beating Eggs.

Beer-pump.—The use of compressed air for forcing beer from barrels, for the retail trade in saloons and hotels, must be more extensive than its use for the air-brake. The air pressure for this service is either provided by hand power or automatically by hydrant pressure.

Bell-ringing, see Ringing Bells.

Bellows, Organ, see Organ Bellows.

Blacksmith's Fires.—Where a compressed-air supply is maintained for operating rock drills or general machinery, and at a pressure of 6 or 7 atmospheres, the air for blowing the blacksmith's fire is sometimes taken from the compressed-air pipes. This is a costly way of supplying air at such a light pressure. The power required for compressing each cubic foot of free air for the rock drill is probably ten times as great as would be required for the blowing pressure.

Blast, Sand, see Sand-blast.

Block Signal, see Switch and Signal Service.

Bessemer Process, see Aerating Molten Metal.

Boiler-shop.—Compressed air is now capable of supplying all the power required for operating boiler-shops, machines or apparatus, mostly portable, being provided for all of the operations involved. Hoisting, punching, shearing, drilling, tapping, reaming, riveting, chipping, caulking, and screwing in and cutting off stay-bolts are all quickly, efficiently, and economically done by compressed air.

Brake, Air, see Air-brake.

Bridge-building.—Compressed air is a valuable assistant in bridge-building, both in the preparation of the material in the shop and in the erection of the structure. In the shop the air is used for hoisting and in portable tools for drilling, reaming, riveting, chipping, etc., as in the boiler-shop. The erection of the bridge would be in many cases impossible without the compressed air in the caissons for the piers, while in the work of erection the portable tools are called in again.

Caisson.—The caisson is used principally for excavations under water, and subsequently for building, in place of the material removed, bridge piers, or solid masonry for any purpose. The caisson is essentially an open box, of a shape corresponding to the purpose desired, closed at the top and loaded above until it sinks where the work is to be done. The caisson being open at the bottom, the water is excluded by the maintenance of an air pressure within, the pressure increasing with the submergence until at a depth of 80 or 100 feet the limit of human endurance is reached. Men and material pass into and out of the caisson by means of the air-lock. The men within the caisson remove the material with which the lower edge of the caisson comes in contact

until a satisfactory foundation is reached, and the caisson is then built up full of substantial masonry and allowed to remain as a part of the permanent structure, which is continued above it to any height desired. The caisson is now also frequently used in obtaining suitable foundations and supports for the tall and heavy office buildings erected in our large cities.

Caissons, Expelling Soft Material from.—This is a use of compressed air entirely distinct from its primal function in the caisson of excluding the water so that the men may be able to work in it. When any soft material is found in the progress of the excavation, it is now customary to expel it through a pipe carried up through the top or side of the caisson, the pressure of the air within supplying all the power required. The pipe is provided with a quick-closing valve, so that when the material has all run out the air may not escape.

Caissons, Operating Air-lock Doors, see Air-lock Doors.

Cars, Propelling, on Street Railways.—Compressed air is not yet extensively used for this purpose in the United States, but is permanently established and successful in Paris and elsewhere in Europe. Experimental cars in the United States show excellent results, and the general adoption of the system in the near future is more than probable. In cost of plant, in facility of introduction, in economy of operation, and in the entire absence of objectionable features the compressed-air system surpasses all others. The principal delay as to its extensive introduction is in determining the ultimately best of many details of construction and operation.

Cars, Dumping.—Cars dumped by compressed air are used in handling earthwork in railroad construction and

similar service, also for coal, ore, limestone, etc. An air-cylinder and piston under the car dumps the load upon either side as may be desired. An entire working train may be dumped at once, or a man may dump each car separately.

Cars, Loading.—One of the functions of the air-hoist or of the pneumatic crane.

Cars, Unloading.—Unloading by lifting the load from the car by the air-hoist instead of by dumping. Oil-tank cars are discharged to a higher level by air pressure admitted to the tank.

Car Roofs, Sanding, see Sanding Car Roofs.

Cars, Cleaning.—This system is now generally used at railroad termini. A supply of compressed air is maintained, and a hose is led into the car or coach to be cleaned, with a nozzle for discharging the air and a cock for regulating or shutting it off. The jet of air is successively passed over the various parts of the interior of the car and the dust and other loose material is driven off at once.

Car Seats, Cleaning.—The seats and cushions, rugs, etc. are removed from the car and, supported upon wooden horses, are thoroughly and quickly cleaned by the air jet.

Car Sills, Pulling Down, see Pulling Down Jacks.

Car Wheels and Axles, Removing, see Removing Car Wheels and Axles.

Carriages, Gun, see Gun-carriages.

Carpets, Cleaning.—The patented arrangement of the writer consists of a grated or perforated level floor or an inclined or vertical surface upon or against which the carpet to be cleaned is spread. The carpet is then traversed by an air-delivery pipe upon wheels and with handles like a lawn-mower. A hose conveys the air to the delivery-

pipe and it emerges in a series of fine jets close to the surface of the carpet, rapidly expelling the dust and dirt. An exhaust fan draws the dust away whether liberated above or below the carpet.

Castings, Chipping.—One of the adaptations of the pneumatic tool, which see.

Caulking.—Now generally done by compressed air, especially in boiler- and tank-work and upon the seams and joints of steel ships. This is another of the uses of the pneumatic tool.

Cash-carriers.—Generally used in the large retail stores.

Canal Locks or Lifts.—An important invention, lifting vessels to any height by a single lift, one air-lift taking the place of several of the old style of locks. As the lift is balanced, but little power is required to operate and little water is lost.

Channelling-machines.—A modification of or more elaborate application of the rock drill, applied either to getting out stone of required shape and dimensions from its native bed, or cutting smooth channels in the solid rock, as at the Chicago Drainage Canal.

Chemical Works.—In chemical works a supply of compressed air is constantly maintained and employed for various uses, such as the pneumatic pump or ejector, the air-lift and aerating processes.

Cleaning.—Compressed air is employed in cleaning various things, such as flues, carpets, castings, by widely different apparatus and processes.

Chipping.—Another of the applications of the pneumatic tool, especially used in boiler-work, bridge- and ship-work, structural ironwork, foundries, etc.

Clipping Horses.

Clocks, Operating.—In extensive use in Paris. Almost the only service rendered by compressed air that could be done as well or better by electricity.

Coal Drills, Operating.—These are revolving drills or augers boring holes very rapidly for light charges of explosives.

Coal-mining Machines.—The cutting tool of the machine reciprocates like a rock drill. It is mounted upon wheels and cuts under the seam of coal to a horizontal depth of five or six feet, when the coal may be broken down and removed.

Coal or Culm Conveyors.

Colors, Spraying.—Used in silk factories for spraying colors upon silk or satin ribbons. A recently perfected process sprays colors upon pottery, sometimes in liquid form and sometimes as a powder. Varied and novel effects are produced by applying several colors simultaneously by separate jets, or color and glazing may be mixed and sprayed together.

Conductor's Train Signal.—Extensively used upon the best railroads.

Cooling.—This is one of the general and widely applicable uses of compressed air. The fall of temperature in compressed air upon release is used for cooling drinking-water, for cooling houses or apartments, theatres, for general refrigeration, ice factories, and cold-storage warehouses.

Copying-presses.

Couplings, Applying, to Hose.

Cranes.—Swinging, jib, or travelling cranes.

Crossings, Gates at, see Gates at Railroad Crossings.

Cupolas, Raising Stock to.

Cutting off Stay-bolts.—This is done by a special style of

portable shears, requiring no skilled labor, and does not loosen the stay-bolt.

Cuts and Quarries, Driving Machinery in.

Dampening Laundry-work.—The spraying-jet takes the place of the Chinaman's mouth, said to be employed for the same purpose.

Dense-air Refrigerating Process.—Used upon warships and elsewhere. The same air is used over and over, compressed to say 15 atmospheres and expanded to say 5 atmospheres, and the same refrigerative effect is accomplished by less power and in smaller compass than when lower pressures are employed.

Direct-acting Hoist.—Quicker and simpler than any other.

Disappearing Gun-carriage.

Disposal of Sewage.—The Shone ejector automatically raises the sewage to give it head to flow where the requisite grade cannot be maintained in the sewer.

Distributing Sand on Locomotives.—Advantage is taken of the air-supply for the brakes, and the tracks are sanded, giving better adhesion and with less waste of sand.

Diving-bell.

Diving-armor.

Doors, Furnace, Raising and Lowering.

Doors, Air-lock Doors, Operating.

Doors, Opening, in Offices and Residences.—This is a suggested rather than an accomplished use of compressed air, but perfectly feasible where the air-supply exists. As we now automatically close our doors, so may we open them in welcome when any one approaches.

Drainage Systems.—Compressed air is variously employed in such service the conditions determining the arrangement.

Dredging.

Drills.—Revolving drills of various kinds, portable drills, metal drills, coal drills, diamond drills for prospecting.

Drills, Rock.—Reciprocating or percussion drills. The use of compressed air employing more of it than any other.

Drinking-water, Cooling.

Drinking-water, Aerating.

Driving Stay-bolt Tops.—One of the special uses of compressed air in the boiler-shop, simple, but saving much time and labor.

Driving Machinery in Shops.—Two or three shops use compressed air for driving all their tools, dispensing with all shafting except a light line for a group of small tools.

Driving Pumps.—An undeveloped use of compressed air of great importance and promise, see Chapter XVI.

Driving Motors or Air-engines.

Drop Pits.—This is the technical name for an arrangement in use in railroad repair shops. The car is run over the pit and an air-jack or hoist lowers wheels and axles to be removed or hoists new ones in place.

Droppers for Cattle.—This name is given to one series of air-hoists used in the Armour packing-house and similar establishments. The bullock, suspended by the heels, after bleeding and decapitation is conveyed by a continuously travelling overhead railway to a hook on one of the droppers, the hook being held up by the pressure of the air with sufficient force to sustain the weight. Upon releasing the air the bullock is dropped upon the floor for skinning, disembowelling and such interesting operations.

Drop Weight for Breaking Castings, Lifting.—A popular use of compressed air in the yards of foundries that are fully equipped with it. A single hoisting cylinder is used

with multiplying sheaves so that the hoist of the weight is usually six or eight times the travel of the piston.

Dry Dock.—The compressed-air dry dock may have all the advantages of the independent floating dock at less first cost and less cost of operation and maintenance.

Dumping Cars.

Dynamite Gun.—The only safe way yet devised for throwing the high explosives. Decided to be of value for coast defence. A number of these guns now under construction.

Eggs, Beating.

Elevators.—Compressed air adapts itself readily to all the various demands of elevator service, and is used for passengers or freight, by direct or multiple lift of a single piston, or with an air-motor with gearing and drums.

Elevators, Coal and Culm.

Elevators, Indicators on.—Indicators operated by compressed air to signal or to inform the passenger and the operator.

Ejector.—Used for automatically transferring sewage or other liquids. The air pressure being maintained, the chamber is alternately filled by the flow of the liquid, and emptied by its ejection or expulsion to a higher level.

Engines, Fire, see Fire-engines.

Engine Works, Driving.

Expelling Soft Material from Caissons.

Extinguishers, Automatic Fire.

Factories, General Use in.—A great and rapidly increasing number of factories are equipped with compressed air, first of all for direct hoisting, and subsequently for various other purposes.

Finish, Satin, on Metal-work, see Satin Finish.

Filtering Water.

Fire-engines.—A suggested use of compressed air, perfectly feasible wherever a general supply of compressed air is distributed.

Fire-extinguisher.

Fires, Blacksmiths', Blowing.

Fires, Kindling.—The aerated oil jet is used in many round-houses for starting the fires in the locomotives at one tenth of the cost of wood kindlings.

Flues, Cleaning.

Forcing Oil.—Transferring oil from tanks to barrels, or *vice versa.*

Foundry, General Service in.

Fountains, Cooling, see Chapter XIII.

Furnace Doors, Raising and Lowering.

Gas, Aerating.

Gates at Crossings, Operating.—In connection with the compressed-air switch and signal service.

Gear Steering, on Ships.

General Hoisting Service.—Some establishments employing more than a hundred air-hoists.

Glass Factories.

Glass-blowing.

Grain Elevators.

Granite-carving.

Granite-cutting.—One of the uses of the pneumatic tool.

Grates, Shaking.

Gun-carriage, Disappearing.

Gun, Pneumatic.—Valuable for coast defence, throwing high explosives.

Guns, Sporting or Target.

Hammer, Pneumatic.

Hardie Car-motor.

Hoisting Cattle, Beef.—Air-hoists used exclusively in the largest packing-houses.

Hoist, Direct-acting Vertical-cylinder.

Hoist, Geared.

Horses, Clipping.

Hose-couplings, Applying.—The machine for this purpose is said to have paid for itself in one day's application of it.

Hydraulic Cranes.—Air is used to give pressure to the water, while the water actually does the hoisting in some lines of service where the elasticity of the air would be objectionable.

Hydraulic Pressure Relief.—In wood-pulp machines in paper-mills a hydraulic feed is employed which is sometimes too positive, and a chamber of compressed air is provided to relieve it and prevent breakage.

Ice-making.

Indicators on Elevators.

Iron, Drills for.

Iron Furnaces, Tapping.

Iron Bridge Work.

Ironwork, Structural.

Jacks, Portable.

Jacks, "Pulling Down."

Kindling Fires in Locomotives.

Lamps.—Aerated oil lamps for street work, railroad operations, etc.

Lard refining.

Laundry-work, Dampening.

Lifting Drop Weight in Foundry Yards.

Locks, Canal.

Lock Doors in Caissons, Operating.

Loading Cars.

Locomotives in Mines, Street Railways, etc.

Locomotives, Kindling Fires in.

Medical Preparations, Spraying.

Mekarski System of Car Propulsion.

Mining Coal.—Compressed air is variously used in coal mines, for "coal-cutters," coal augers, rock drills, pumps, hoists, etc.

Mixing Nitroglycerine.

Moulding-machines.—In the foundry compressed air rams or presses the sand in the moulding-machine, lifts the mould, draws the pattern, etc.

Nitroglycerine, Mixing.

Operating Air-drills and Punches

Opening Doors.

Packages, Transmitting.

Painting.

Pile-driver.

Pits, Drop, see Drop Pits.

Physicians' Spraying Apparatus.

Pneumatic Ejector.

Pneumatic Press.

Pneumatic Signal for Railway Trains.

Pneumatic Tool.

Pneumatic Tubes for Transmission.

Portable Drill.

Portable Jack.

Preserving Timber, the Wood Vulcanizing Process, which see.

Press, Copying.

Press, Straightening.

Pottery, Spraying with Colors.

Process, Bessemer, see Aerating Molten Metal.
Pulling Down Jacks, see Jacks, Pulling Down.
Pump, Air-Lift.
Pump, Automatic.
Pump, Beer.
Pumps, Operating.
Pumping Acids.
Punch, Portable.
Punching in Boiler-shops, etc.
Quarries, General Work in.
Railways, Street.
Railroad Shops, Various Uses in.
Railroad Shops and Sheds, Whitewashing.
Raising Stock to Cupolas in Foundries.
Raising Ships.—Air-tight bags are attached all around a sunken ship, or placed by divers in the hold, then inflated by compressed air, and, acting like balloons in the air, when their combined displacement is sufficient the ship rises.
Refining Lard.
Refining Asphalt.
Refrigerating.
Removing Mandrels.
Removing Scale from Steel Plates—another of the uses of the pneumatic tool.
Ribbons, Spraying with Colors.
Ringing Bells on Locomotives.
Riveting.
Rock Drills, Operating.
Rock Tunnels, Driving, All Operations in.
Sand-blast.

Sanding Tracks.—Giving better distribution, better adhesion, and wasting less sand than where delivered by gravity.

Sanding Car Roofs.—A process used in the car-building or repair shops in connection with the painting of the roofs of freight cars. The sand is delivered by the air with force, so that it embeds itself in the paint, forming a protection for the surface. What is not held by the paint is removed by the same blast of air that delivers the sand.

Satin Finish on Metals.—Used on plated work for railroad cars.

Scale, Removing, from Steel Plates.

Seats, Cleaning.

Sewage Disposal.

Sheathing Pile-driver.

Sheep-shearing.

Ships, Raising.

Ships, Steering.

Ships, General Service on.

Shops, Driving Machine Tools in.

Signal, Block.

Signal, Conductor's.

Silk Manufacture.

Silk Ribbons, Spraying.

Skates.

Soft-ground Tunnels.

Spraying Laundry-work.

Spraying Colors on Silk Ribbons.

Spraying Colors on Pottery.

Stay-bolts, Cutting off.

Stay-bolt Taps, Driving.

Steering-gear on Ships.

Stone-cutting.

Storage, Cold.
Steel Plates, Removing Scale from.
Street Railways.
Structural Ironwork.
Switches and Signals on Railroads.
Syrups, Agitating.
Taps, Driving, in Boiler-shops.
Tapping Iron Furnaces.
Testing Brakes.
Timber, Preserving.
Tires for Vehicles.
Tool, Pneumatic.
Torpedo Service.
Tracks, Sanding.
Train Signal.
Transferring Oil or Acids.
Transmitting Packages.
Transmitting Power from Waterfalls.
Travelling-crane.
Trucks, Dumping.
Tunnels, Soft-ground.
Tunnels in Rock.
Turrets, Operating on Warships.
Unloading Cars.—This is done either by hoisting, by dumping, or in tank cars by pressure upon the service of the liquid.
Ventilating.
Vertical Direct Hoist.
Vehicle Wheel-tires.
Warfare, General use in.
Water-balloon, see Raising Ships.
Water, Raising.

Water, Aerating.
Water, Filtering.
Wheels and Axles, Hoisting or Removing.
Whitewashing.
Working Turrets.
World's Fair Painting.
Wood Vulcanizing.
Works, Chemical, General use in.

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